Climate-responsive design for non-domestic buildings in warm climates : optimisation of thermal mass for indoor cooling

Thesis

CLIMATE-RESPONSIVE DESIGN FOR NON-DOMESTIC BUILDINGS IN WARM CLIMATES

Optimisation of Thermal Mass for Indoor Cooling

Camilo Diaz

A thesis submitted in partial fulfilment of the requirements of the Open University for the degree of Doctor of Philosophy

October 1994

Architectural Association Graduate School

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ABSTRACT

The present investigation focuses on the study of the thermal inertia of buildings examining the extent to which the envelope and internal components can moderate their internal climate. Especial emphasis is given to the analysis of thermal mass effects in conditions of overheating in buildings with predominantly day-time occupancy schedules such as offices and mixed use buildings.

The thesis comprises three parts. The first part discusses the principles and definitions of thermal inertia identifying a number of aspects which are relevant to the thermal performance of buildings. A review of the physical principles and parameters for quantification of heat storage in building elements is also included. The second part presents the results obtained from a series of field experiments carried out in six buildings in different locations to observe the thermal reaction on their internal spaces according to the particular thermal mass characteristics of each case.

The third part is devoted to the analytic work by means of parametric studies and by comparing the field experiments findings with computer simulation results and exploring additional aspects of thermal mass effects. The analytic studies included the application of the diurnal heat capacity method for the calculation of internal temperature swings obtaining results in close agreement with both SERI-RES simulations and field measurements. A calculation worksheet is proposed to facilitate the internal swing calculations. Finally, the conclusions obtained from the results were used to define a series design measures aimed at the improvement of indoor thermal conditions by the optimisation of the effect of thermal mass of buildings in warm environments.

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Introduction

The relationship between climate and comfort can be viewed within two important categories: The energy form and the structural form. The former controls the environment through dynamic and flexible resources (such as fire when is used against the cold). The second refers to the defence or environmental selection through static systems such as the roofs and walls of conventional buildings. The content of this investigation is concerned with the second category.

Climate has been ever since primitive existence, one of the generating forces of architecture. However, the historical evolution of man and its living environment has often forced the architectural product to respond to pressures of economic, technological and cultural nature. In this respect, the degree to which architecture has been responsive to climate derives directly from the interrelation between these factors. In conditions where technological development has led architects and building professionals to neglect climate as an integrated element of the architectural process, it has been observed that the requirements for thermal and visual comfort in buildings, particularly of those from the so-called modern period, have been met mainly by sources other than those provided by the natural environment. Only then, inhabitancy in those buildings has been made possible. Unfortunately, that has been the predominant nature of contemporary architecture in most parts of the world.

Traditional forms of architecture on the other hand, have often shown an intrinsic preoccupation for the natural provision of comfort in buildings as part of man's basic necessity for shelter, especially in locations of extreme weather conditions. For this reason, climate in traditional buildings is usually a major component and a generator of their own architectural expression. However, recent attempts in recognising traditional knowledge in architecture have failed to interpret the real values and motivations behind aspects of building geometry and use of materials. Examples of pseudo-vernacular architecture commercially exploited, often inappropriate, can be found virtually everywhere. People's lifestyles have changed and former building materials and technologies may not be suitable any longer. The authentic reassessment on architectural attitude towards traditional values should be oriented to the essence of vernacular architecture rather than the simple replication of formal elements. In this respect, a scientific understanding of the factors governing building physics and environmental exchanges emerges as compulsory if architects are to redefine their design approaches. Only then, the lessons from traditional practices in architecture can effectively be implemented.

The use of thermal mass in buildings to moderate the extremes of the external climate inside of buildings is one of the aspects of traditional construction which has been widely recognised by designers of contemporary buildings. A long experience on the application of thermal inertia techniques has been left by many generations of various cultures of the world with different constructional methods and in various climatic regions. The increasing interest among architects and building scientists in different countries to improve the quality of the built environment has led to a wide range of research and experimental projects aimed at improving the understanding of the effect of thermal inertia of buildings.

The benefits of the effect of thermal inertia of the building mass have been used empirically in many traditional edifications both in warm and cool climates. Massive building envelopes and dense urban grids have been used to attenuate the large temperature fluctuations of hot and arid regions helping to maintain houses warm in winter and cooler in summer. More recently, research on the use of thermal mass in cooler locations has led to experimental implementation of heat storage techniques from direct radiation to reduce heating requirements in residential buildings [5].

The shortage of numerical evidence on the optimisation of thermal inertia effects for reducing the cooling requirements of buildings in regions with long overheating periods has also been raised recently and a number of research and architectural projects are increasingly being undertaken to widen the scope of information available and to improve the existing knowledge [19], [20]. The present research project aims at providing further data and analytical results obtained from experimental studies in real buildings and from computer simulations in an attempt to provide a better understanding of the optimum use of thermal mass of buildings in warm climates.

Part I
Definitions and Principles

1
Building Mass and Indoor Climate

1.1 The Building as a Climate Moderator

In most climate types the building envelope can moderate the internal climate by storing heat and delaying its transfer to the interior. The selection of the thermal properties of the building elements and the appropriate judgement regarding the quantity, location and distribution of the systems of the building's thermal inertia will contribute to control its internal climate. Large temperature swings, usually beyond 10 K, are likely to cause thermal discomfort to the human body by making it feel either too cold or too hot or because of a large thermal variation occurring within a short period of time. The thermal mass of the building envelope and other building elements will be able to reduce this temperature range to a degree which is dependant on various factors, two of the more important being the thermal storage capacity of the building and the extent and duration of heat gains.

The building thermal mass is made out of all building components, walls roof and floors, although the heat storage effect may be different from one element to another. The building envelope will store heat coming both from the external environment, mainly from direct and reflected solar radiation and from internal heat gains. Depending on the properties of the envelope mass, external heat will be stored and transferred to the interior by conduction. Heat from direct radiation can also be stored directly onto internal surfaces depending on window location and orientation. This is particularly useful during the cool periods when day-time storage can help to return useful heat at night. In periods of overheating, direct radiation falling on internal surfaces should be avoided in order to minimise the total heat gains inside the building. However, even if solar gains are avoided, heat gains will be produced internally inside the building mainly from occupants, lighting and mechanical equipment. A large proportion of this heat will be absorbed by the internal mass and the temperature swings reduced as a result.

1.2 Regulatory Functions

Heat storage occurs to one extent or another in any building and in any location. In regions where the temperature variations during the day is large, the benefits of heat storage can fulfil dual functions, reducing overheating during the day while providing needed heat at night. Heat storage and distribution throughout the building mass is a complex process which depending on the characteristics of the building elements can be of long duration, extended over a long period of time (days, weeks or months) or it may have a rather temporary effect. It is a frequent constructional practice to build a massive envelope and place lightweight partitions for the internal layout, particularly in office buildings. Most of the long term storage of heat (one day or more) will occur through the envelope while the internal mass will store heat for a few hours only. This may not always be desirable as heat storage in internal elements can be significant for the overall thermal performance of the building. This is discussed with more detail in the following chapters.

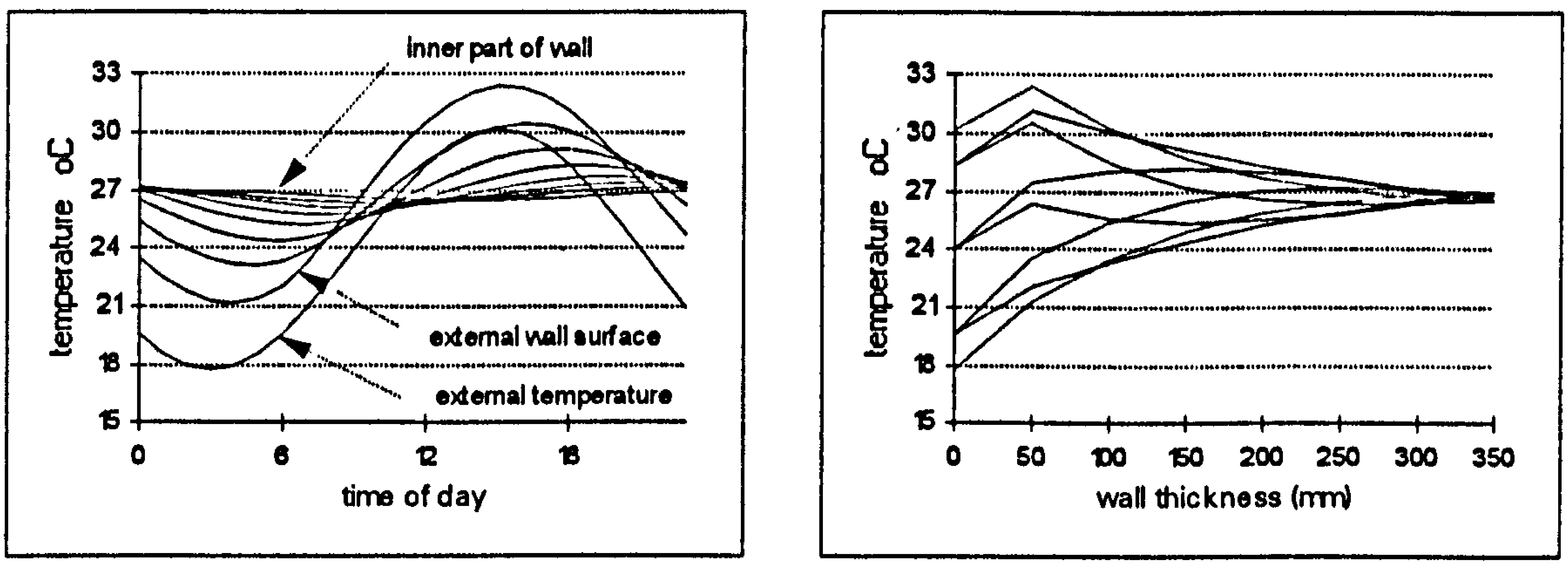
In climates with large diurnal ranges of temperature the envelope of the building is used to attenuate the effect of direct radiation and the external air temperatures. Heat will be carried in through the structure and it will reach the internal surfaces at a later time. This, together with additional sources of heat produced internally and from ventilation will tend to raise the internal temperature. The internal mass elements such as partitions, stairwells, mezzanines, etc. can help to further moderate the internal climate by absorbing a large proportion of heat from internal gains resulting in an increase on the mass surface temperatures but reducing the temperature of the air.

When the building is well insulated and the problems of overheating result mainly from excessive internal gains, it is often practical to increase the thermal capacity of internal walls. A well insulated envelope however may take longer to cool down when air temperatures drop since the thermal insulation will force the heat stored on the inner layer of the wall to flow one-dimensionally toward the inside. An increased air movement near the internal surfaces will assist this process for which the use of fans is usually recommended.

Internal mass elements absorb heat on both surfaces if these are well exposed to the internal air. The amount of heat absorbed depends on the temperature difference between the surfaces and the air, the thickness of the element and the thermal properties of the materials, especially of those closer to the surface. The addition of thickness in homogeneous walls will increase proportionally the total thermal capacity of the elements although the amount of heat flowing into the material will not increase proportionally in situations of periodic temperature fluctuation. Very thick walls are not very effective for heat storage and release in a periodic cycle because the deeper regions of the walls which are thermally remote from the surface cannot effectively participate in the heat exchanges taking place during the 24 hour cycle between the air and the thermal mass.

The temperature fluctuations at the centre of a very thick wall between spaces with similar temperature will tend to be zero indicating the inefficient role of unexposed mass of building elements.

With variations according to the properties of the materials used, there is a wall depth to which heat can penetrate and return to the surface in a period of one day and beyond this thickness the effectiveness of the wall in terms of thermal inertia will not be increased despite its higher thermal capacity.



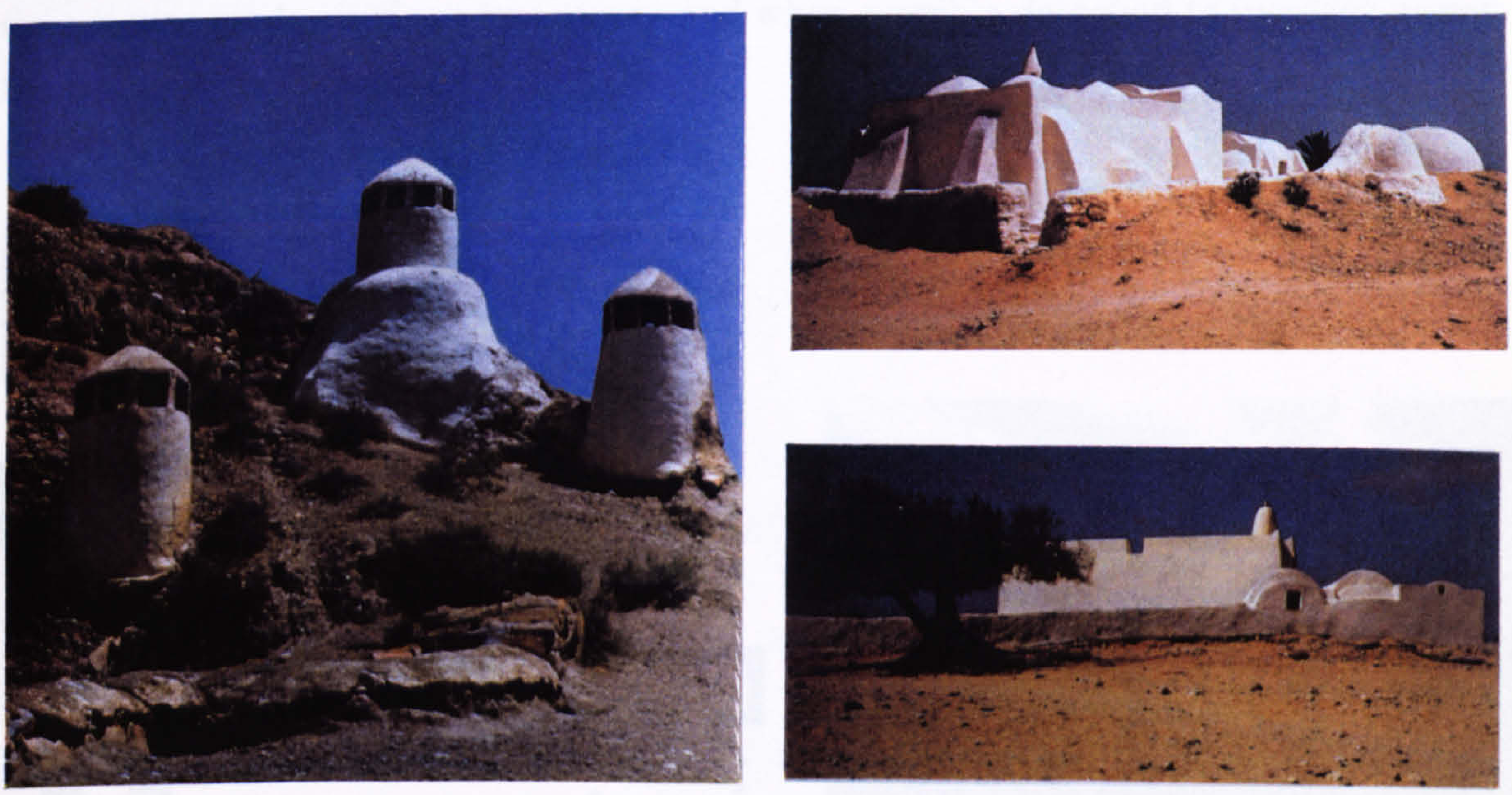
a) temperatures at various depths in to wall *b) temperatures at different times of the day*

1.1 Temperature profile of a massive wall. The charts illustrate the small temperature variations at the inner layers and the higher fluctuations at the outer layers. Based on simulations for a thick brick wall in sunny weather.

Excessive thickness may produce the effect of heat that continued to flow inwards after the diurnal cycle will reappear when the air temperature is rising again the day after, reducing the effective storage capacity of the wall. The diurnal response of the thermal mass for heat storage in buildings is discussed in chapter 3.

1.3 Intuitive Expertise and Vernacular Tradition

One of the most important characteristics of the effect of thermal inertia of buildings is the time lag resulting from the thermal storage. The long term storage, for periods over two months or one entire season is associated with very thick and massive buildings, mostly found in historic sites and also in underground houses and cave edifices traditional in various parts of the world. The large time lags related with such massive structures make the building become warmer in winter and cooler in the summer. A significant proportion of the heat that is stored in the mass of the envelope and internal walls during the hot season travels through the structure and is released several months later, when the average external temperature drops. In these buildings the internal temperature is often near to constant throughout the year at a level close to the average outdoor air temperature. A survey in a number of cave dwellings in Tripolitania in North Africa, showed the internal temperatures remaining within a few degrees of 19 °C even though the extreme air temperatures range from -6 °C to 42 °C [59]. Massive buildings to this extent are particularly useful where the average external temperature is within the comfort zone but it would be undesirable in locations with a predominantly cold climate because the internal temperature would remain too low most of the time.

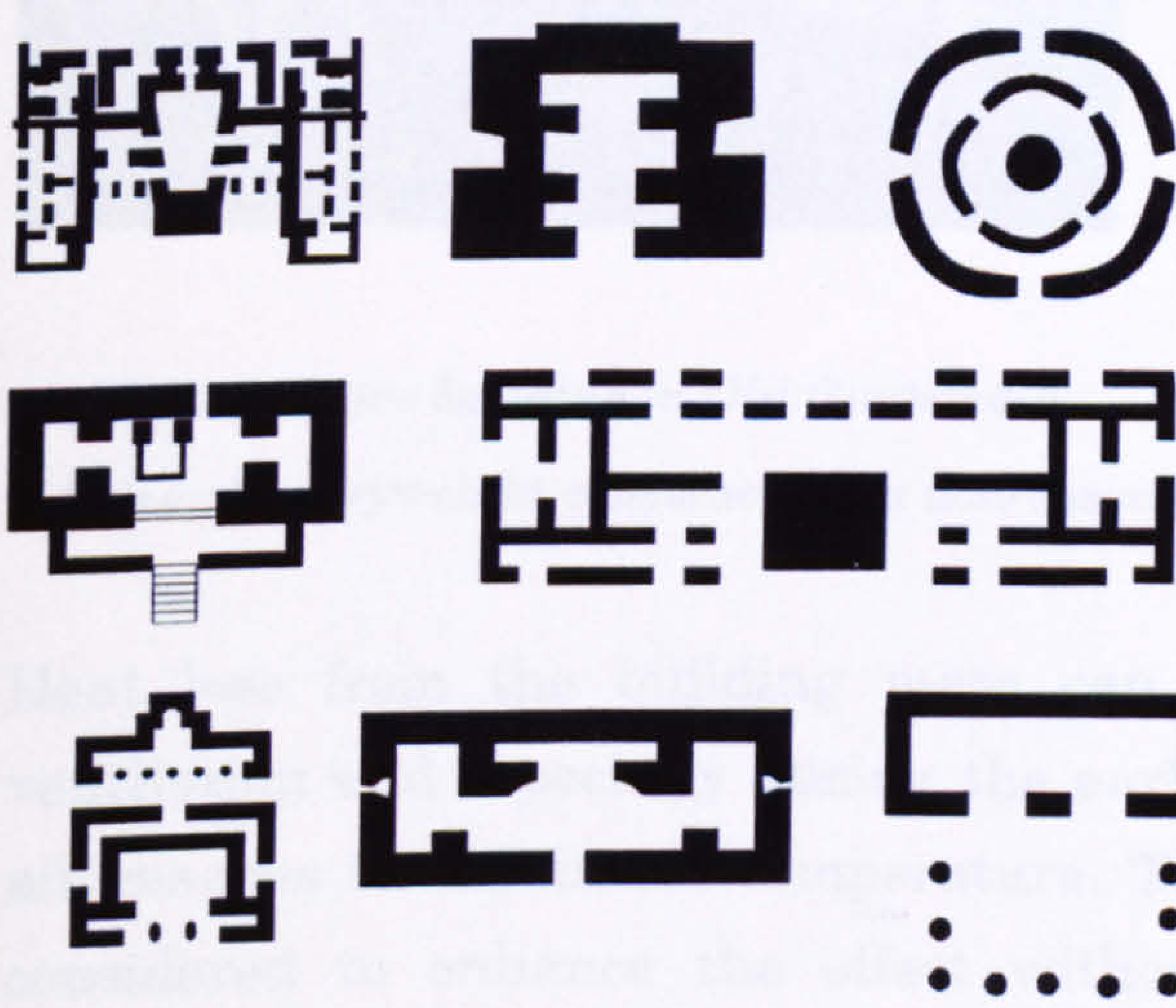


a) Chimneys of underground dwellings, Spain *b) Heavy walled mosque, Tunisia.*

1.2 Underground building in Sierra Nevada, southern Spain (a), where a tribe of Gypsies have scooped caves out of the hillside and established a community of some ten thousand people. b), a religious temple in the island of Djerba, off the southern Mediterranean coast of Tunisia. Source, [72]

Massive buildings exist in many regions of the world with a variety of climate types, although not always for the same reasons. It is also frequent to find massive construction even in locations where these are not necessarily considered the most appropriate from the climatic point of view, for example in some tropical humid areas. The first settlers in the ancient pre-Hispanic America constructed a large number of temples, houses and other edifices in various cities throughout the continent using blocks made of the local stone for the massive walls and roofs.

Several centuries later, the Spanish introduced new technologies of construction and planning, including the courtyard brought to them previously by the Arabs, and other elements such as the arcades, the verandas, eaves etc. but the massive character of the buildings remained a predominant feature. Thick adobe walls and clay tiles for roofs and floors are still widely used in various parts of Central and South America particularly in residential buildings and in rural communities. The introduction of foreign architectural elements was not implemented without climatic adaptations; for example, the courtyard usually a tight enclosure in Arab buildings, was enlarged especially along the east-west axis to minimise incident radiation on these facades and instead of the typical four storey Arab house in a dense urban area it was made single or two storey and when possible detached to increase access to breeze on all directions.



a) Ground plans of Mayan buildings source: [79] *b) Typical house Old Guatemala*

1.3 Ancient and Colonial use of massive construction in Central America.

In regions with relatively small diurnal ranges of temperature such as those of warm humid climates, heat from solar radiation is absorbed by the surfaces of roofs and walls and released at night when the temperatures drop. The diurnal process of heat storage- heat release in these conditions is somewhat slowed down by the small temperature difference between the night air and the building mass. For this reason it is often recommended for these locations the use of lightweight materials for the building envelope so that heat release from the structure can be more quickly promoted.

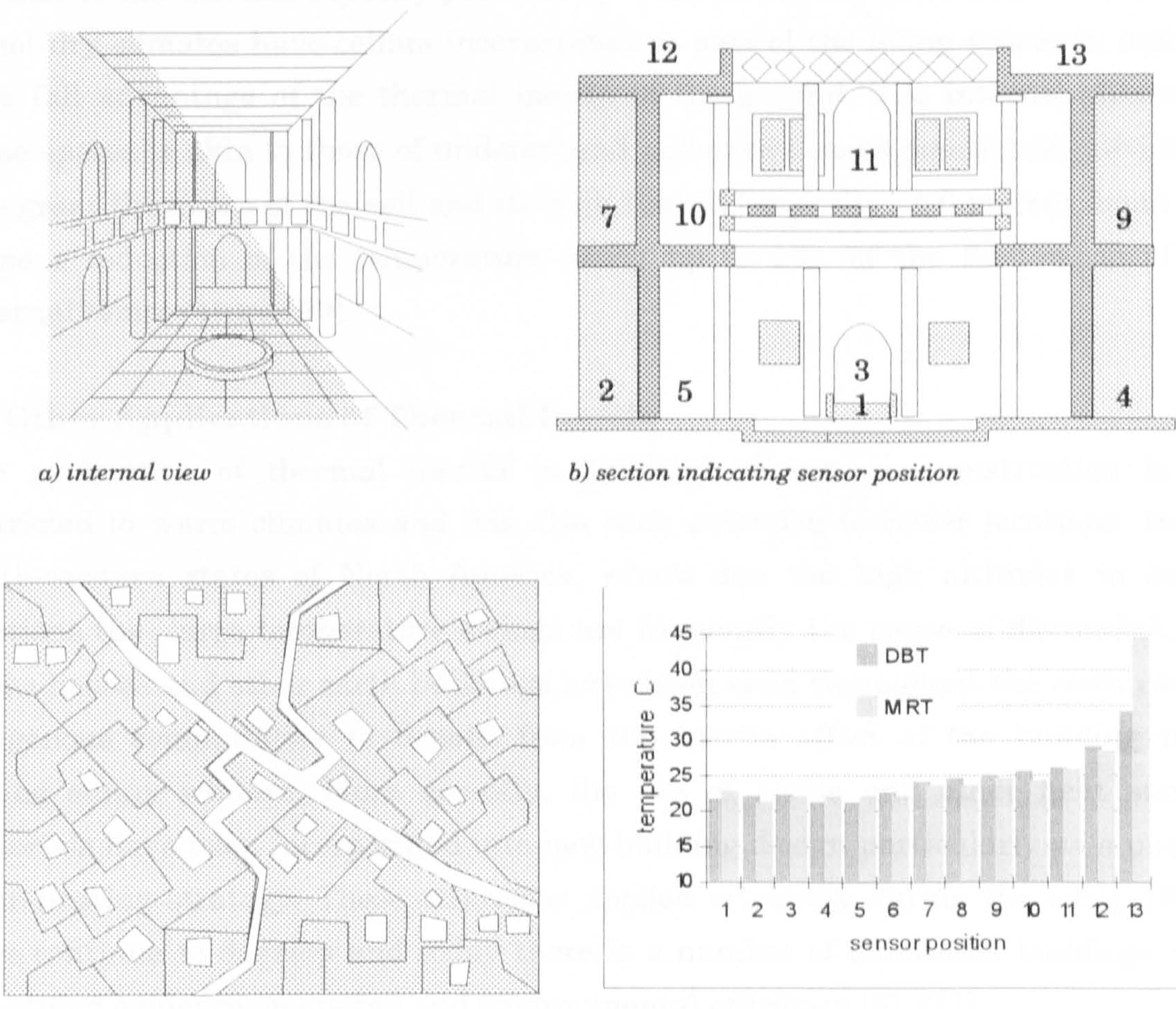
The use of massive elements in warm humid climates however may be advantageous, particularly in buildings with a predominant day-time occupancy pattern. The peak internal temperature in these situations will be reached some time after the external temperature has reached its maximum value, usually at or soon after mid-day, delaying the overheating hours for a later time of the day when the building is no longer occupied. Heat dissipation from the structure before the next day begins should be ensured.

a) Administrative building in Old Guatemala *b) Recreational building in Montelimar, Nicaragua*

1.4 Use of heavyweight construction in non-domestic buildings in warm humid locations.

Heat loss from the building mass can be accelerated by increasing night-time ventilation and especially during the early hours of the morning when the outdoor air reaches its minimum temperature. The design of openings should be carefully considered to enhance the effect without affecting other concerns such as the problem of security. The benefits of thermal mass in warm humid climates are also taken advantage of in residential buildings by making the day-time occupied spaces of the house such as the living and dining rooms with high thermal storage materials and leaving the bedrooms and private areas with lightweight quick thermal response building elements. This arrangement is also convenient in mixed used buildings where commercial or office activities take place at the ground floors and the night-time occupancy areas in the upper stories.

Most of buildings in hot dry, Mediterranean and other predominantly warm locations, although with a wide variety of architectural features according to specific location, typology, constructional tradition and particular climate variations, are built with massive materials. In dessert climates where the prevalent clear sky conditions for most of the year makes the heat absorbed on the surfaces to re-radiate quickly to the night sky creating large diurnal fluctuations of temperature, the use of very thick stone and earth blocks for the envelope and internal walls of buildings is a strong and widely spread tradition. The old towns in the Arab regions of Asia and northern Africa are typical examples of the traditional use of the effect of thermal inertia at both, individual building and urban levels.



a) internal view *b) section indicating sensor position*

c) urban grid of the old city *d) spot temperature measurements*

1.5 Spot temperature measurements in a courtyard house in the old city of Fes, Morocco.

The outdoor conditions of these locations is sometimes so hostile that life takes place almost entirely indoors and in semi-outdoor spaces. The streets are made narrow to protect the vertical surfaces from solar radiation and usually walkways are covered with the use of arcades, colonnades and small enclosed courtyards. A series of spot temperature measurements taken in street courtyards, walkways and internal patios in the old town of Fes, Morocco indicated that external climate is completely modified by the massive structures of the inner areas of the city, 1.5.

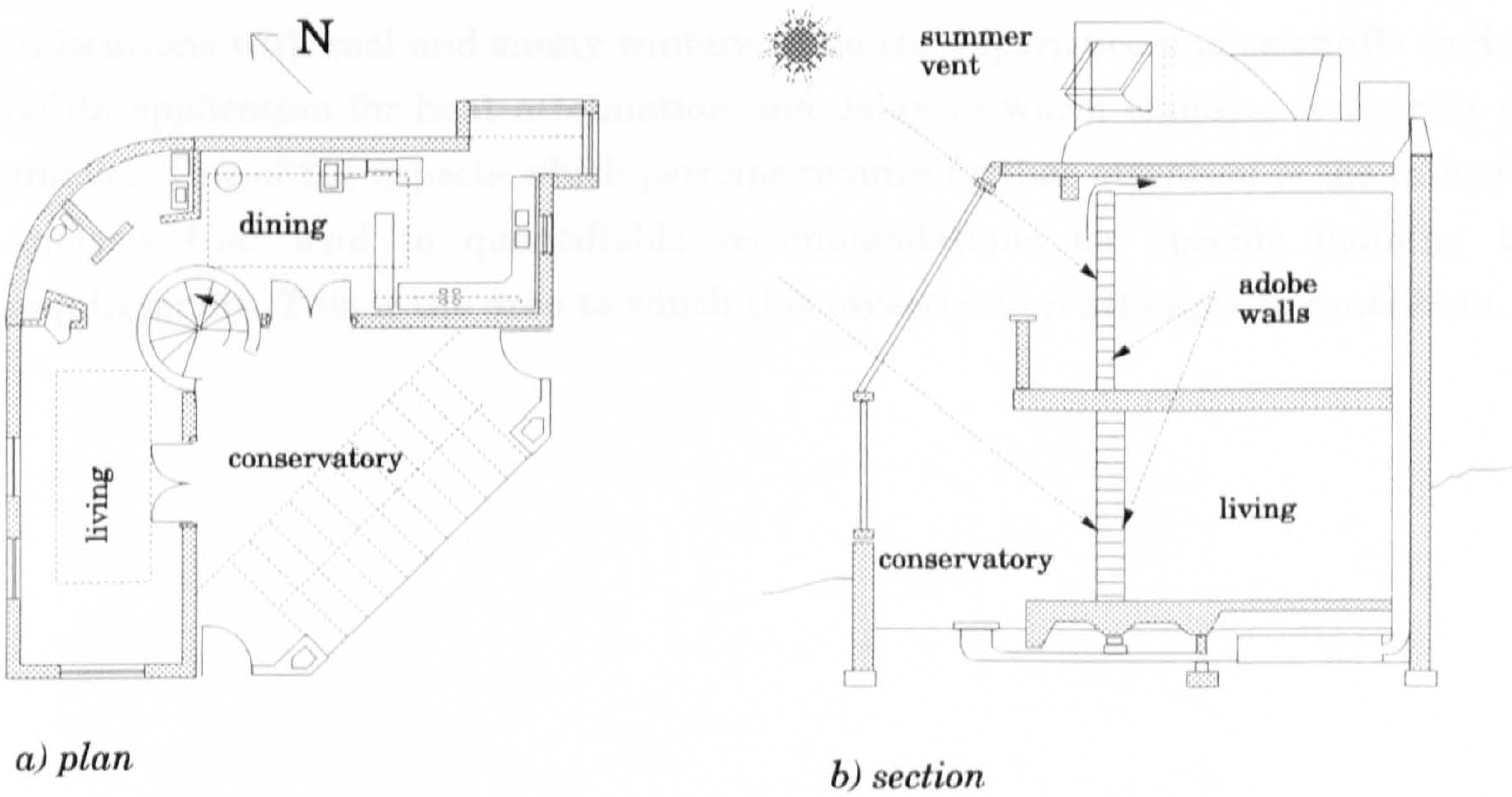
A difference up to 10 K was observed between the temperatures of outside and inside the boundaries of the *medina* (old city) during the warm periods of the day. Due to the density and thermal protection of the town, in many spots the sun is hardly seen and although it is somewhat dark, the temperature has a small diurnal range.

Further to the thermal capacity provided by walls and roofs, some traditional houses in hot dry climates have cellars incorporated as part of the living spaces in order to take full advantage of the thermal inertia of the ground. The internal climate of these spaces is akin to those of underground and cave houses mentioned previously. The great thickness of the soil and its high thermal capacity at 6 meters depth will cause a reduction of the temperature swing up to 1% of the fluctuation of the external temperature [59].

1.4 Other Applications of Thermal Inertia

The application of thermal inertia in buildings of massive construction is not restricted to warm climates and has also been extended to cooler locations. In the south-western states of North America, where due the high altitudes in desert locations the large temperature swings are frequently the cause of discomfort, the adobe houses and other earth buildings have been used throughout the centuries by indigenous communities to benefit from the inertia effect of the building mass during sunny winters. More recently, the use of adobe and other heat storage materials have been incorporated into new building design particularly as a passive solar heating strategy. These strategies applied originally during the early 1970s, have continue to develop and today there is a number of monitored buildings with quantified evidence on energy and environmental efficiency [5], [71].

In these buildings, the effect of heat storage on massive internal elements can be enhanced by the use of glazed surfaces such as sunspaces large windows and trombe walls, in order to maximise and to direct the incidence solar radiation on the internal surfaces. The heat absorbed and stored is re-radiated toward the inside at a later time during the evening when the internal temperatures fall and some heating is required. It is important that the storage walls are well exposed to the sun rays and that surfaces are not covered with objects such as paintings, shelves, furniture or other pieces of furniture since this would reduce the effectiveness of the wall. The direct beam-radiation solar radiation received by the wall is approximately the size of the glazing area. This portion of the wall will be the warmest for some time but after a few reflections, especially if the surfaces are of light colours, the heat will be redistributed within all the surfaces in view maintaining the temperatures fairly uniform. Heat will also be redistributed by convection to other surfaces of the house which are not exposed to direct radiation, carrying warm air which is then deposited in the rest of walls and ceilings [5].



1.6 Use of thermal inertia in a passive solar house in New Mexico, US. *From [5]*

Conclusions

The effect of thermal inertia in buildings is the process of heat storage, heat distribution and heat dissipation that occur in the walls and roofs of buildings over a certain period of time. Heat is stored in massive elements causing a reduction on the internal temperature swings and a delay of peak temperatures.

The envelope and internal elements of buildings store and release heat direct from solar radiation and indirectly from internal gains. Heat storage takes place in one way or another in buildings of any type regardless the climate and whether it is planned or not. The control over this mechanism should be a principal design target in order to optimise the thermal performance of the building. Because the effect of thermal mass can vary according to properties of materials, building form, orientation, location and occupancy patterns, it is necessary to seek optimum performance considering all the influencing variables for each specific case.

The effect of thermal mass in buildings has been extensively used throughout the centuries in various regions of the world and its benefits are widely recognised and applied in contemporary architecture.

Research on the use of thermal mass has also been extensive and a number of findings have been reported, [1, 2, 4, 5, 8, 21, 27] and others. Most of the information available however focuses on the thermal inertia benefits for buildings in locations with cool and sunny winters while the experience and scientific evidence on its application for heat attenuation and delay in warm climates is a great deal smaller. One of the aspects which perhaps require further attention is the numerical analysis that lead to quantifiable recommendations for specific building type requirements. This is the area to which this investigation attempts to contribute.

2

Principles of Thermal Inertia

2.1 Thermal Mass of Buildings - Definition and Functions

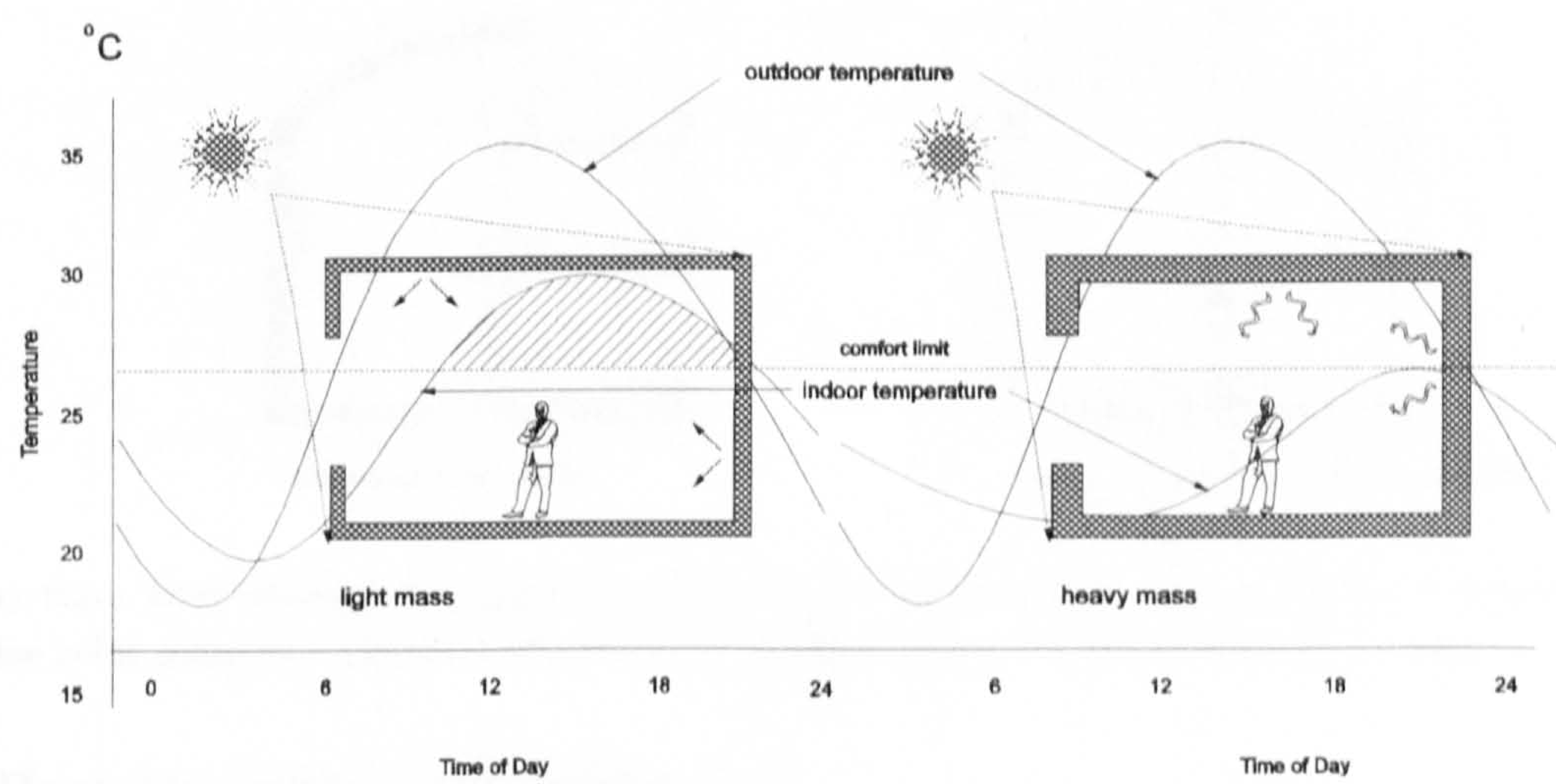
The quantity and distribution of thermal mass play a decisive part in the thermal characteristics of buildings and can strongly influence the conditions of indoor comfort due to the effect of its thermal inertia. The optimisation of the effect of the thermal inertia of buildings has been defined by various authors as a primary design target for overheated climates [4], [17], [19] and for passive solar heating [5], [21], [26], [28]. The thermal mass and its thermal effect is a major component of the building and although it requires careful study, it should not be treated in isolation but as part of a global design strategy. This is to say that in conditions of overheating, optimisation of thermal mass in buildings should start to be considered after all measures reduce heat gains have been taken [6].

The thermal and energy conservation advantages attached to the optimisation of thermal mass in buildings vary according to the design criteria adopted and on the particular location, climate and materials used. In locations with cold but sunny winters, the utilisation of thermal mass effects can lead to substantial contributions in space heating by the efficient use of thermal storage materials [5], [51]. Cooling load requirements in summer or in predominantly warm locations can also be minimised with the inertia effect of massive buildings.

2.1.1 Heat Attenuation and Delay

One of the most significant attributes of thermal mass in buildings is the influence it can exert on the internal temperature swings and consequently on thermal comfort. Even when comfort throughout the day cannot be obtained, the judicious selection and placement of the building mass can make significant contributions to thermal comfort inside the building or minimise energy requirements where heating or air conditioning is used. Heat absorbed by the building mass during the day can be stored for a number of hours and then released when the outdoor temperature drops at night-time. In free-running buildings, the extent to which this process can be manipulated to improve the thermal performance of the building depends largely on the decisions taken during the design stages. These will have to be made in accordance with the building type, the occupancy patterns, the availability of materials and the characteristics of the climate. The indoor climate of a building will be further affected by the form, the degree and the occurrence of internal gains (occupants, lighting and equipment).

In locations of frequent hot weather, day-time temperatures inside office or commercial buildings often reach maximum levels during periods of high occupancy bringing distress to the users. This is usually the case in poorly insulated or low thermal mass buildings where the heat storage capacity is not sufficient to create the necessary time delay in heat flow through the structure. As the envelope is radiated by the sun throughout the day, heat will reach the interior in a few hours. The introduction of natural ventilation in those situations may only add to the problem by further increasing the internal temperature or/and the relative humidity, depending on the external conditions. Large capacity air-conditioning systems are frequently used to alleviate this problem incurring in substantial levels of energy consumption. The use of larger heat storage capacity materials and the external protection in the building envelope will in principle delay and reduce the internal peak temperature.

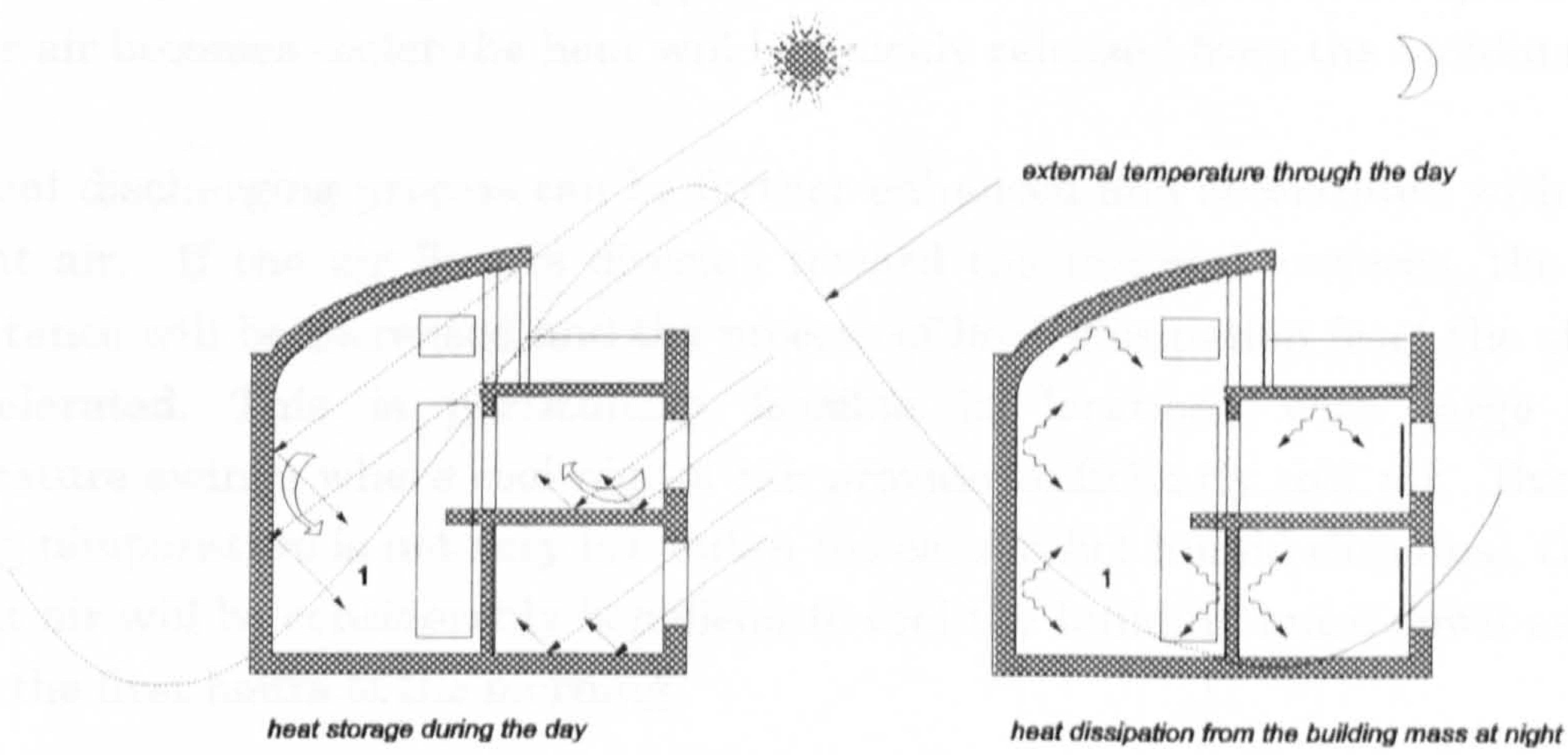


2.1 Effect of the thermal inertia of the building mass on the internal temperature of day-time occupied rooms.

2.1.2 Dual Thermal Functions

In locations with predominantly overheating problems, design measures should be taken in order to avoid direct solar gains through non-opaque elements. The benefit of the thermal inertia of the building would be lost or greatly affected if shading or adequate insulation is not provided. Careful design decisions should also be made to ensure that solar exclusion devices do not put at risk the ingress of daylight to the interior of the building.

The same physical principles that make the use of thermal mass in buildings an efficient design strategy during the overheated periods, are those which make it an effective technique for the winter. In locations with cold but sunny winters the use of heat storage in the building structure can be of significant advantage for night heating. If efficient solar control measures are taken, the internal surfaces of the building will be exposed to direct solar gains through glazed elements. The heat absorbed by the internal building mass will be stored temporarily and then released at a later time when the demand of heating load is the highest. An efficient manipulation of this process by the design can result in large reductions or in many cases the elimination of the heating requirements of buildings. Heat storage techniques for solar heating have been widely applied in various parts of the world with reported evidence of energy efficiency and thermal improvements [5], [53].



2.2 Day-time heat storage for night heating during the winter. Solar control measures should minimise solar gains in summer while ensuring the exposure of sunlit surfaces in winter.

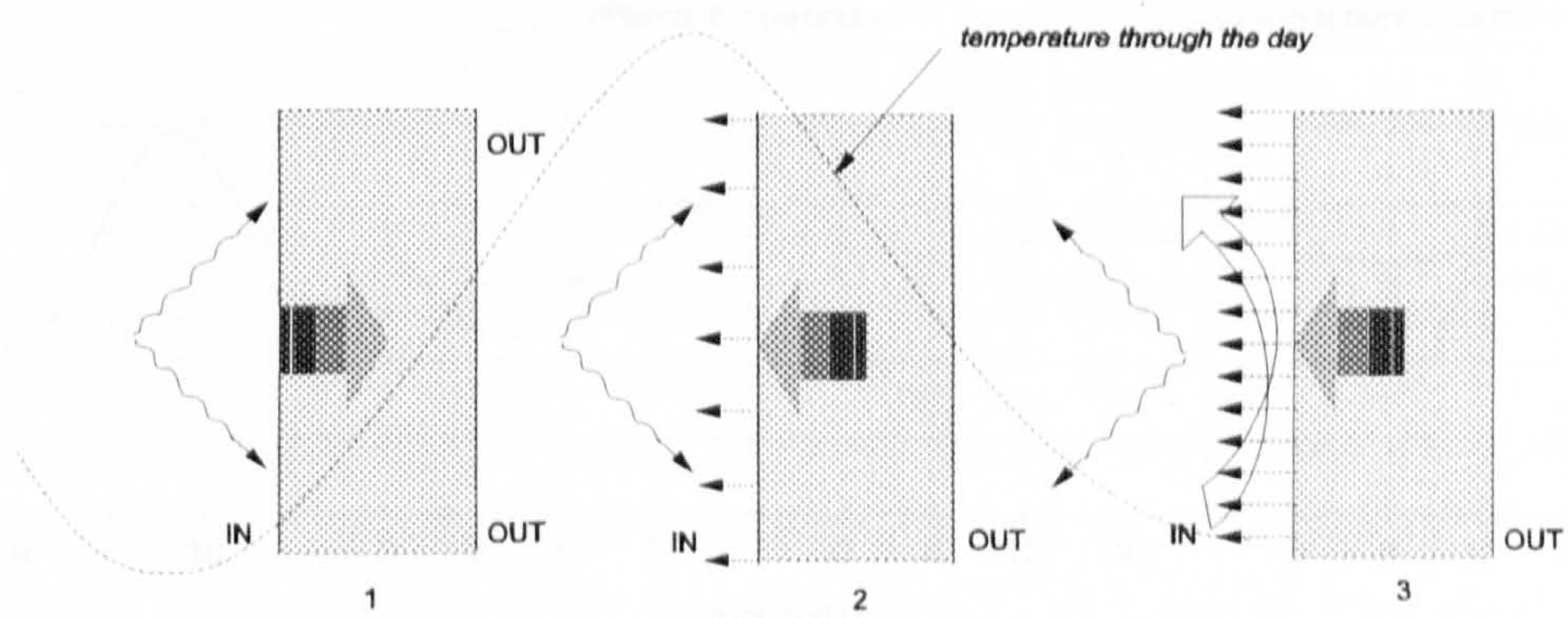
2.1.3 Heat Absorption and Dissipation

The variation of climatic conditions creates a repetitive thermal cycle with a duration of 24 hours. This diurnal variation in temperature makes the building absorb heat from the external environment during the periods of high temperature and lose it during the cool periods. As the sun rays make contact with the building surfaces, heat is absorbed and conducted through the structure. Each portion of the building element will be heated up by contact with the previous portion and heat will continue to penetrate as long as there is a heat impulse activating this flow. When the air temperature drops, the direction of the flow will be reversed. During this process most of the heat will be dissipated from the structure to the air in a period of 12 hours. Depending on the type and thickness of the materials, there will be portions of heat that will be stored for longer periods.

The process of heat dissipation from the structure is governed by the conductivity of the storage material and the temperature difference between the structure and the air. A third component is the conductance of the air film near the surface of elements. This will vary according to the property of the surface material and on the velocity of air passing near the surface.

One of the most relevant aspects within the process of heat storage and dissipation as an efficient mechanism to control the internal climate of buildings is the occupancy schedule. For example, in buildings which are unoccupied at night-time, in warm environments the heat stored in the walls, floors, partitions and roofs during the day will be released back to the interior of the rooms where the heat source is no longer present. As a result, the indoor temperature may rise beyond a comfortable limit but this will happen when the building is unoccupied. As the outdoor air becomes cooler the heat will be quickly released from the building mass.

This heat discharging process can be further enhanced and accelerated with the use of night air. If the air flow is directed toward the internal surfaces, the surface conductance will be increased and the process of heat dissipation from the structure is accelerated. This is particularly feasible in locations with large outdoor temperature swings where cool nights can provide sufficiently cool air. Even if the evening temperature is not very low (often the case in hot humid climates), the effect of night air will be considerably beneficial to cool the building mass down especially during the first hours of the morning.

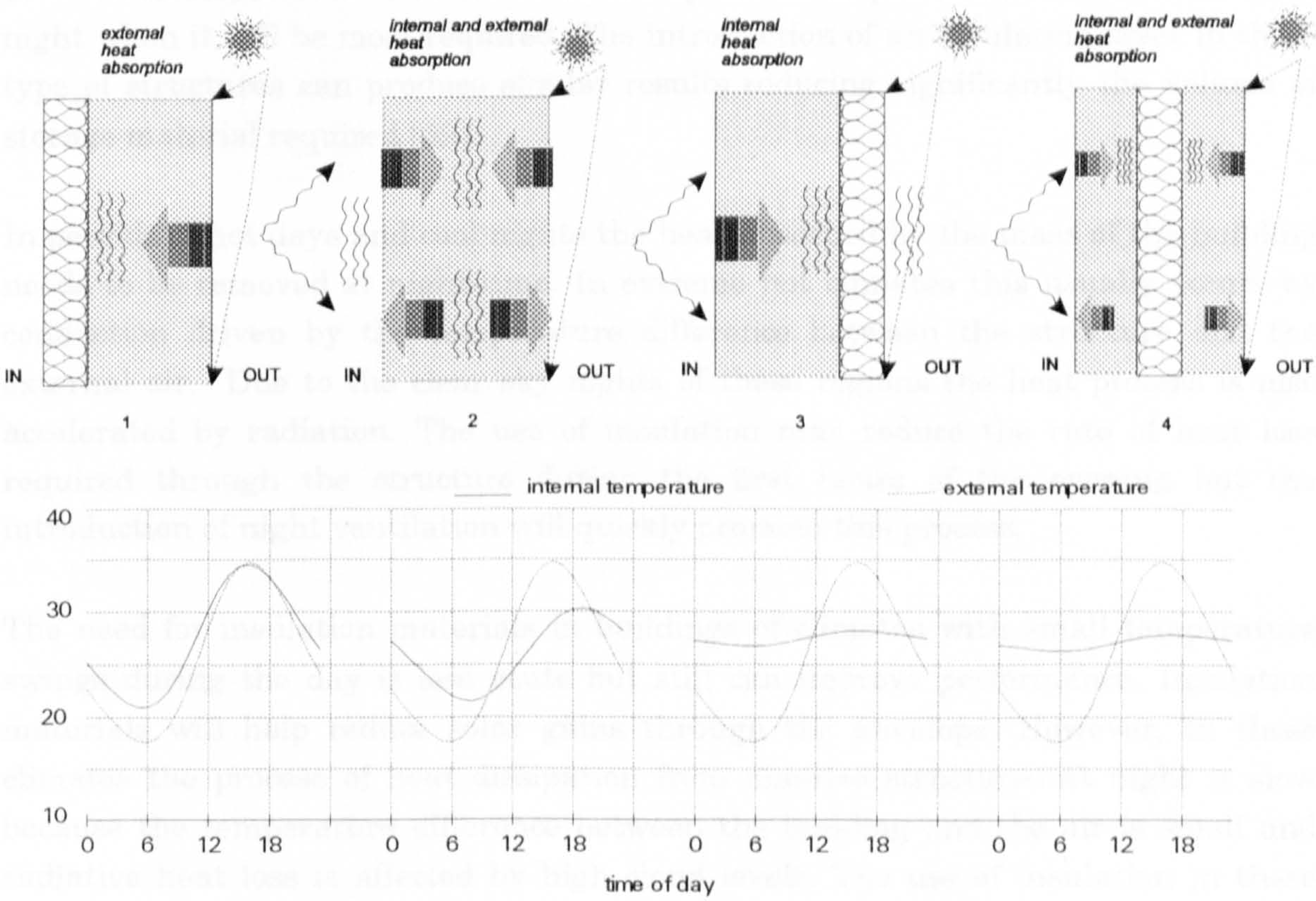


2.3 Heat storage and heat release in and from walls and roofs. The cycle is determined by the thermal properties of the wall materials and the temperature conditions surrounding the surfaces. Heat loss rate from the wall can be promoted by increasing the surfaces conductance through convection .

During night-time when air speeds are usually lower, the use of fans can help to speed up the process of heat dissipation by increasing the heat transfer coefficient of the internal surfaces.

2.1.4 Heat Storage and Thermal Insulation

The thermal characteristics of insulation materials are contradictory to those of the materials commonly used for heat storage. However, the combined use of thermal insulation and massive materials in walls and roofs can improve the performance of buildings. Low conductivity materials will reduce the transmission of heat from one side of the structure to the other, but the placement of an insulation layer within a wall or roof has to be carefully considered. If an insulation layer is located at the inner side of the wall or roof, heat from direct solar radiation will be absorbed and stored by the building mass of the envelope. Although its flow inwards will be restricted by the resistance of the insulation, inner sided insulation will provide little storage capacity for heat gains produced internally. In this manner during periods of cold weather, the useful heat stored by the mass will be lost to the environment at night.



2.4 Effect of location of insulation in massive walls and roofs. Based on simulations for Seville for a single-zoned cube with a 300 mm concrete envelope.

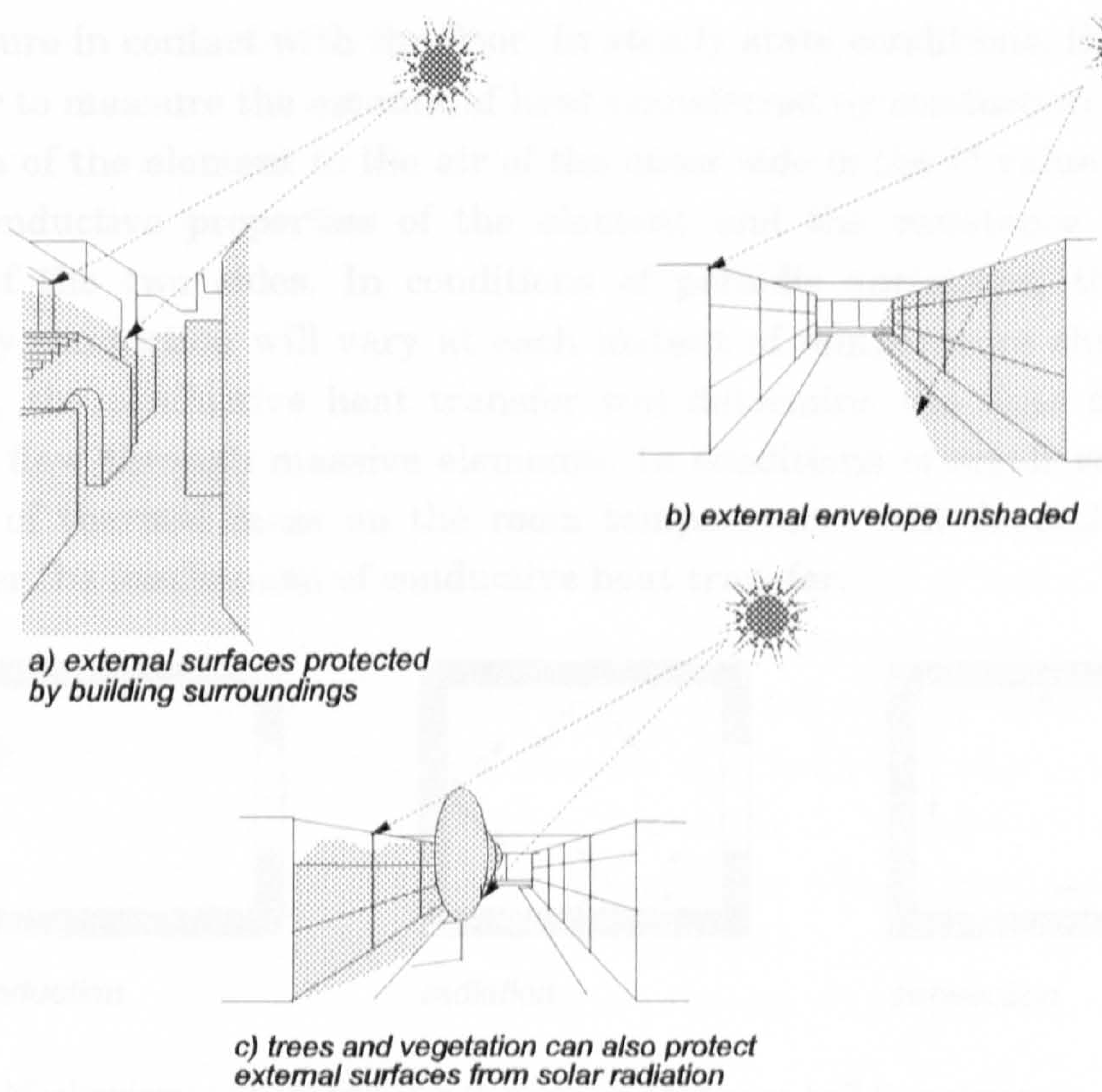
The placement of insulation on the outer side of the element will reduce considerably the absorption of heat from solar radiation. The use of reflective finishes can improve this effect. This arrangement will also allow the inner mass of the envelope to absorb internal gains or solar gains when required. This effect can be improved by high absorbance finishes but this may affect daylight. The most common practice in various countries is to place the insulation layer near the centre of the wall, with the greater thickness for the outer solid layers. This will give a compromise in performance between the two previous cases.

In uninsulated elements heat storage will take place freely and the direction of the flow will be dictated by the variations of temperature during the day. If the external environment is dominated by strong solar radiation, heat will be absorbed and conducted through the building envelope to the interior at a later time. This is an old traditional practice in various parts of the world, particularly in extreme climates where the temperature fluctuation during the day is large. In these locations the use of massive uninsulated envelopes create a time lag of, for example 10 or 12 hours, so that the heat absorbed by the mass penetrates into the rooms at night when it will be most required. The introduction of an insulation layer in these type of structures can produce similar results reducing significantly the volume of storage material required [59].

In periods of hot days and cool nights the heat absorbed by the mass of the building needs to be removed at night-time. In extreme hot climates this usually occurs by conduction driven by the temperature difference between the structure and the external air. Due to the clear sky nights of these regions the heat process is also accelerated by radiation. The use of insulation may reduce the rate of heat loss required through the structure during the first hours of the evening but the introduction of night ventilation will quickly promote this process.

The need for insulation materials in buildings of climates with small temperature swings during the day is less acute but still can improve performance. Insulation materials will help reduce solar gains through the envelope. However, In these climates the process of heat dissipation from massive structures at night is slow because the temperature difference between the building and the air is small and radiative heat loss is affected by high cloud levels. The use of insulation in these particular situations will further impede this thermal process and the introduction of night ventilation will be crucial to provide the heat loss required from the structure before the start of the new day. If insulation is used in these climates the placement outside the envelope will be the most advantageous, both to protect the building mass from direct radiation and to promote heat absorption from internal gains to internal surfaces.

In addition to insulation of the structure, further protection to the building envelope especially walls and windows is frequently provided by trees and vegetation and surrounding buildings. In high density urban areas, the use of narrow streets and walkways help to minimise sun penetration to vertical surfaces and some times solar protection of the roof from adjacent buildings is also possible. In these areas the use of green areas on the building surrounding grounds will also contribute to the reduction of reflected radiation to the building surfaces.



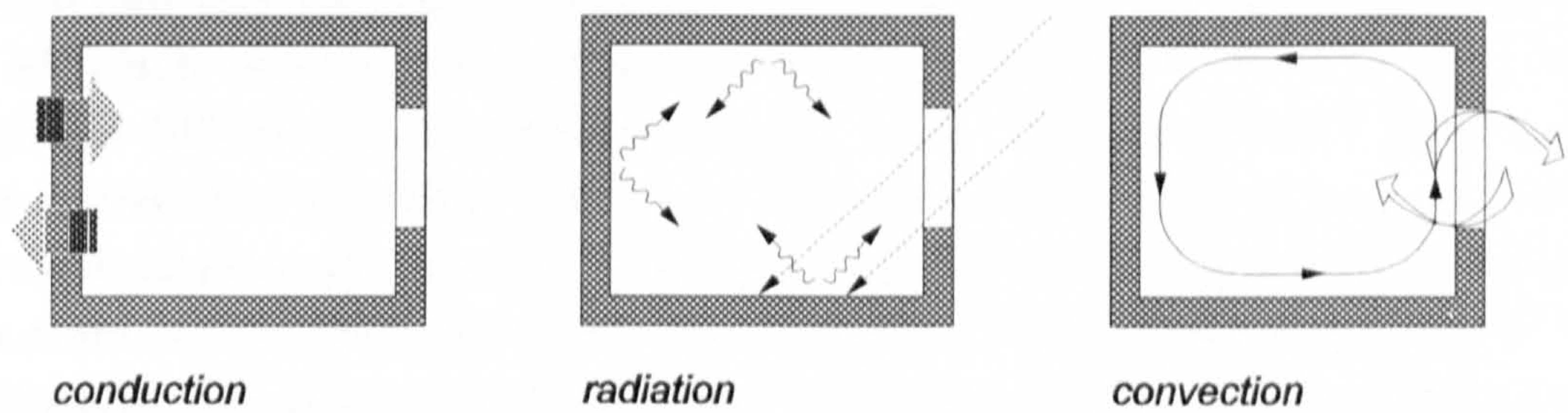
2.5 Protection of the building envelope against direct radiation.

2.2 Principles of Thermal Inertia

The form in which the thermal mass can affect the thermal reaction of buildings dictated mainly by three physical principles: heat transfer, heat storage and heat distribution. In principle, any building in any location will be subject to these three processes in one way or another. Depending on the type of heat source, heat will be conveyed over building surfaces where some will be absorbed and some will be reflected depending on the characteristics of the surface. Once the first fraction of heat has been delivered into the building, the mechanisms of heat transfer, heat distribution and heat storage will begin to take place according to the thermo-physical characteristics of the building mass and the external environment.

2.3 Heat Transfer

The mechanisms of heat transfer between surfaces are governed by three thermal principles: conduction, radiation and convection. Heat by conduction occurs between the particles of mass which by contact to each other transmit a unit of heat for every fraction of temperature rise. The rate of this transfer is determined by the magnitude of the heat impulse over the surface, and by the conductivity and specific heat of the material. Heat transfer by conduction is also associated with the heat exchanges between bodies in direct contact with building surfaces such as people and furniture in contact with the floor. In steady state conditions, the most common parameter to measure the amount of heat transferred by conduction between the air of one side of the element to the air of the other side is the U value which accounts for the conductive properties of the element and the resistance of cavities and surfaces of the two sides. In conditions of periodic variations, the rate of heat transfer by conduction will vary at each instant of temperature shift. Under these conditions, the conductive heat transfer will determine the time delay associated with heat flow through massive elements. In conditions of small ventilation rates, the effect of thermal mass on the room temperatures will depend largely on the control over the mechanism of conductive heat transfer.



2.6 Mechanisms of heat transfer through and between building elements

Heat exchange by radiation between surfaces will follow the arrival of any form of radiant energy into a system. In most situations, the radiative transfer of heat is by far the dominant mechanism of heat exchange between surfaces whether this is in the form short-wave or infra-red radiation. Internal surfaces of buildings open to direct radiation will absorb energy and depending on its colour it will re-radiate heat to the surrounding surfaces within view. The receiving surfaces will re-radiate back infrared radiation until a heat balance is obtained within the space. If direct solar radiation is excluded inside a building, internal sources of heat will also radiate heat to the surrounding surfaces and the heat exchange process is repeated.

In a heated room, the predominant form of heat exchange between surfaces is by radiation. However, a smaller but significant proportion of this exchange carried out through convection. In the absence of heating or cooling of the air, the temperature difference between the surfaces induces a circulation of air. Air rises along the warmest wall and returns down along the coolest surface. This usually creates convective loops of moving air around a room or building although in principle warm air will tend to stay close to the ceiling producing a temperature stratification. Air does not absorb much radiation therefore its temperature is hardly affected by the radiative exchanges between the walls. The convective part of the heat density, in contrast will have a direct effect on the temperature of the air because it is a good heat transport mechanism and it is in fact by convective exchanges between the surfaces and the air that room temperatures change. It is also due to convection that the surfaces which are located away from the heat source will receive a proportion of heat.

2.4 Heat Storage

Thermal storage is the temporary reserve of high or low temperature energy for later use. In terms of sensible heat, thermal storage is accomplished by rising or lowering the temperature of the storage means, usually water, rockbeds, brick or soil. In passive buildings these temperature excitations are produced mainly by solar radiation and internal gains. Most thermal storage applications involve a 24-hour cycle although weekly and seasonal storage is also used. Establishing storage duration is difficult but in principle, storage should not be charged earlier or to a higher degree than required. The use of thermal mass for heat storage in buildings has a dual purpose. It can store desired heat that can be re-used later in the day or it can store temporarily unwanted excess heat which will be removed later in the day. Usually, the design emphasis made by the application of one strategy or the other will determine the form of the building and the characteristics of its components. It is also frequent the need for a combined solution so that the heat storage strategy works in both the overheating and the underheating period.

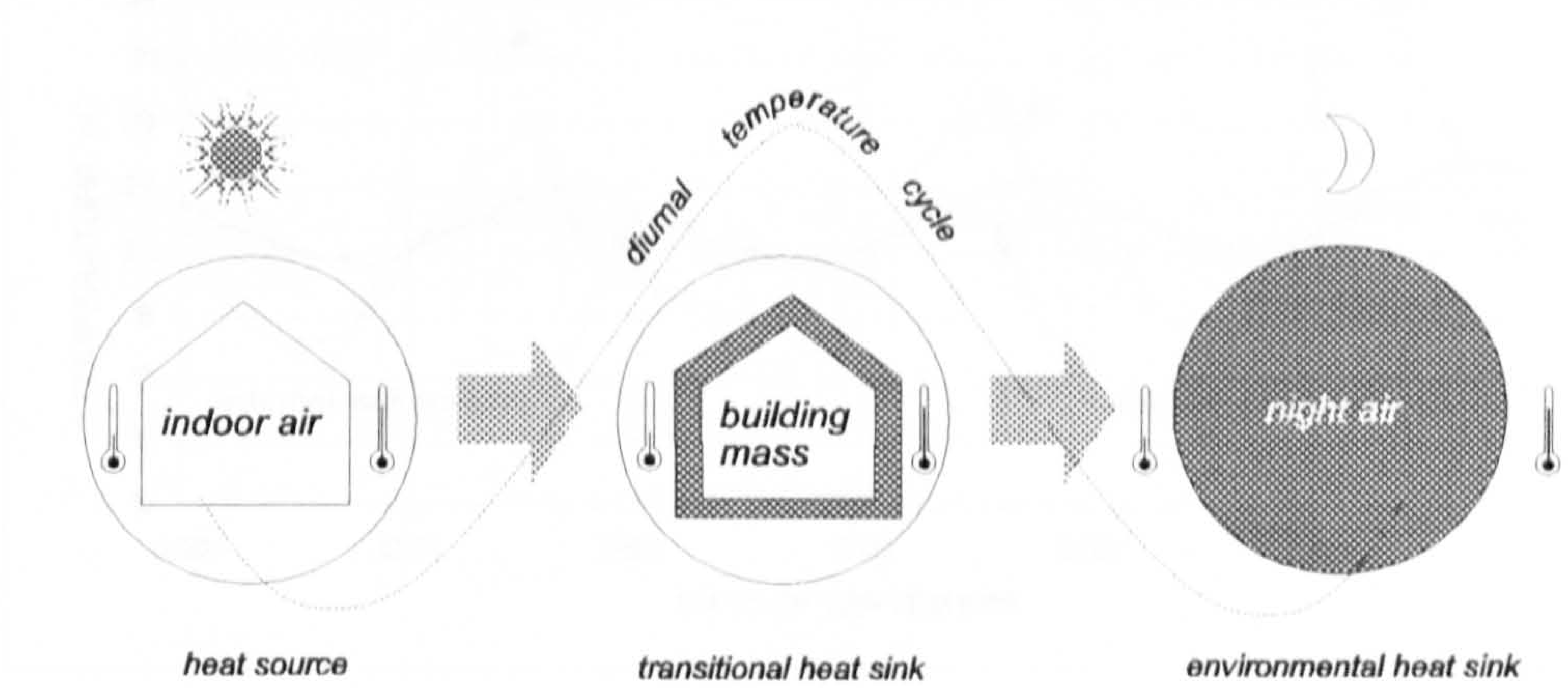
In latent heat storage, this process takes place by a change in the physical state of the storage medium, usually from liquid to solid. This is the principle of phase change materials. Typical materials of this kind are water/ice, salt hydrates and certain polymers. Phase change materials have the advantage of approximately 80% less volume than that of water. Recent studies have shown the potential of phase change materials using a PCM gypsum composite with encouraging experimental results for heat storage in buildings [57].

2.4.1 Heat Storage in Overheating Situations

In conditions of overheating, when outdoor temperatures exceed 30 °C, even after all measures have been taken to reduce heat gains inside buildings, there is always a considerable proportion of excess heat produced especially from internal gains, and often from infiltration and from reflected and diffuse radiation, which if not dealt with, can be the source of thermal discomfort. The most desirable situation of heat storage in warm conditions would start from the exclusion of all forms of heat gains from the external environment. The making of such a scenario presupposes firstly, the incorporation of a strict solar control system through glazed elements which compromises between shading and daylighting, secondly, a protected envelope which prevents the flux of heat through the structure into the inside space and thirdly, the reduction of day-time ventilation gains. This will result in a situation where the bulk of the heat gains in the building are generated internally. If the external air is warmer than the internal, the only heat sink available in a case like this is the building itself and possibly the ground. This is where heat storage becomes a design target.

2.4.2 Internal Mass as a Transitional Heat Sink

The underlying assumption behind the concept of cyclic heat storage and dissipation whether this is diurnal or for a longer period, is that the building mass used for storage during the charging period, will be discharged completely before the next cycle. Failure to ensure this would result in the reduction of the effective storage capacity of the building and this will be followed by the increase of the mean internal temperature. This is to say that mass alone will not guarantee the effectiveness of thermal inertia in buildings for day-time cooling. While the building mass is used as a heat sink for the day-time internal gains in the building, the structure will use the night air as its environmental heat sink when the building mass becomes the heat source. In this picture it is possible to imagine a heat sink chain during the storage and dissipation cycle:



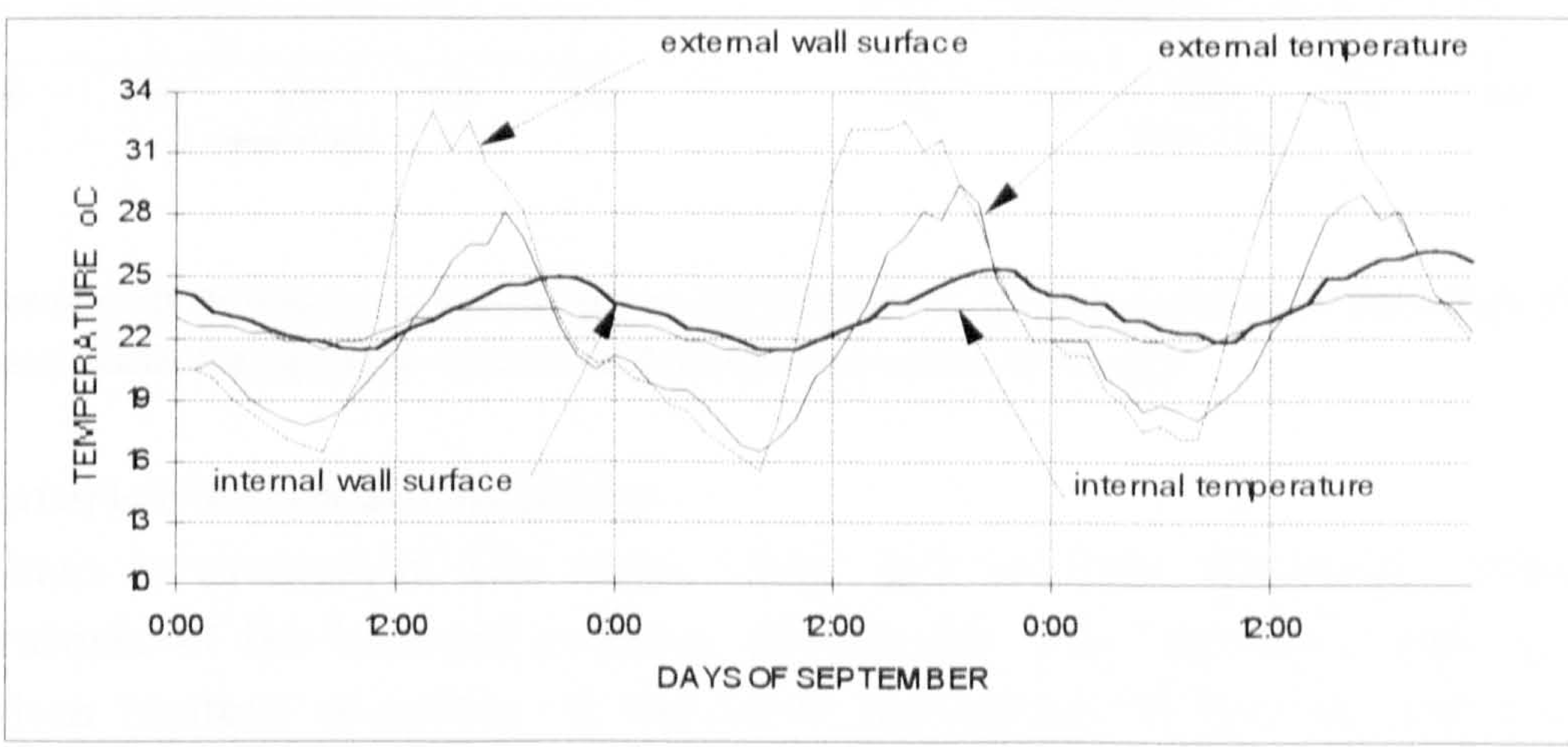
2.7 Heat sink chain formed during the process of heat storage and dissipation in a diurnal cycle.

2.4.3 Effect of Surface Temperatures

The external surface temperature will be affected by the degree of incident radiation building orientation, and the characteristics of the finishes like for example colour and texture. In unventilated and shaded spaces, the daily patterns of air and surface temperatures can give an indication of the measure of heat being transferred through the envelope and the proportion of heat being stored in the building mass. The estimation of the heat flow from temperature measurements at the wall surfaces is also possible [31]. After heat has been released inside a room by any of the three mechanisms defined, the process of heat storage on the surrounding mass will start. The type of material and conditions of the surface of building elements will determine the magnitude and the duration of this process. In the context of an unheated room the daily variations of external temperature is attenuated at the inside surfaces producing a time lag, the extent of which will depend on the penetration depth of the wall material. The penetration depth corresponding to a 24 hour cycle varies depending on the material but normally it does not exceed 200 mm. With thicker walls, the 24 hour temperature cycle at the internal surfaces will become negligibly small.

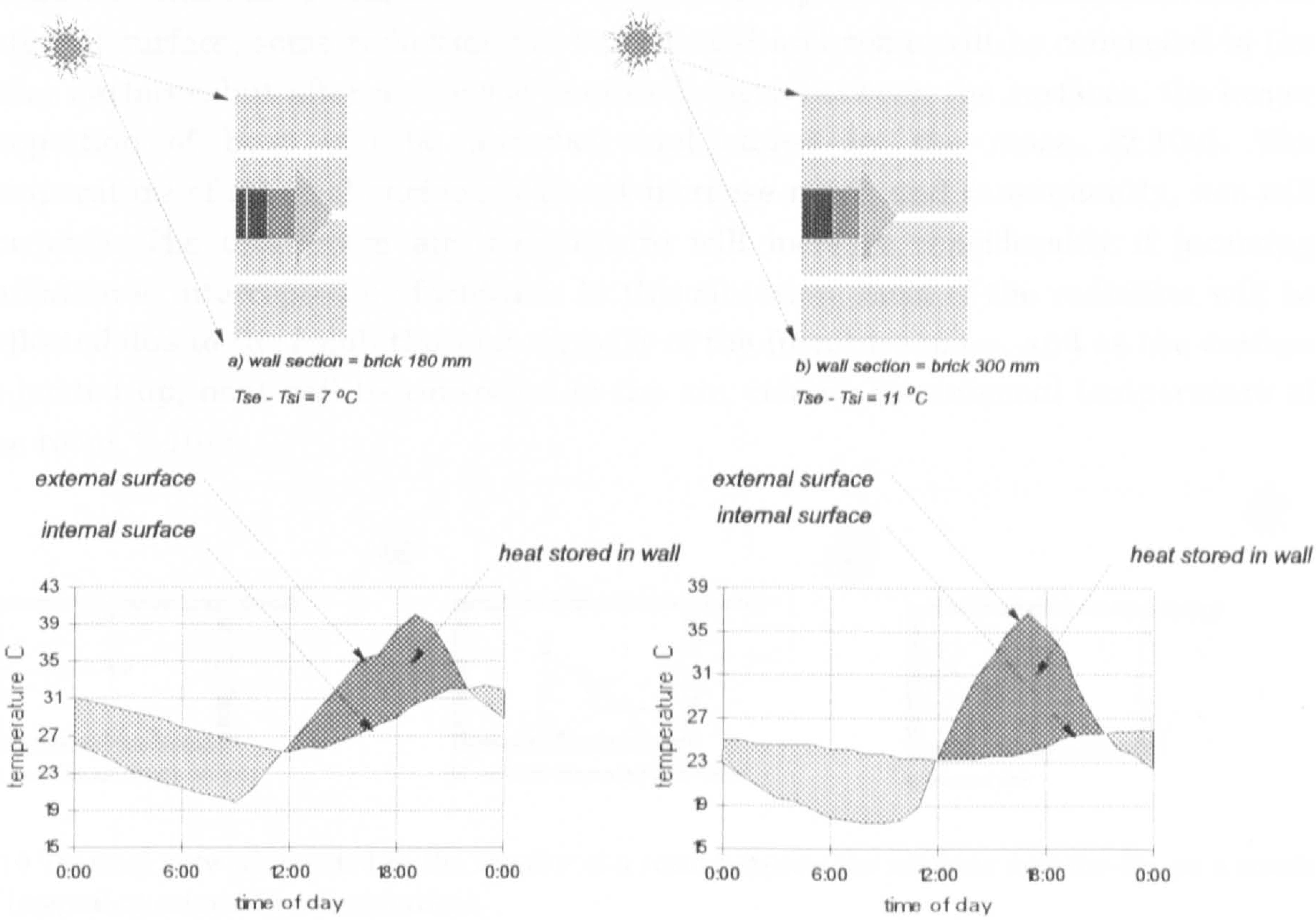
2.4.4 Thermal Characteristics of Internal Surfaces

Ideally in overheating conditions, the internal surfaces should always be maintained cooler than the air so that they can continuously absorb heat. This will depend on the quantity and the thermal properties of the materials at the surface and on the response of the building envelope to the effect of external temperature and solar radiation. Additionally, the appropriate use of a heat sink, for example the night air, is also an influencing factor.



2.8 Typical thermal response of an insulated south facing wall. Data from field measurements in Seville.

The response of the building fabric to solar radiation depends on the overall conductance and heat capacity of its elements. Thick walls can absorb a large amount of heat and less heat will be conducted inwards to the structure. In this situation, the external surface temperature will be lower. Thin walls absorb and conduct heat to the inside but as the thermal capacity is smaller, they will store less heat and the excess will tend to elevate the temperature of the internal surface. In these cases the thermal conditions of the room will be governed by the variations on external temperature and solar radiation.

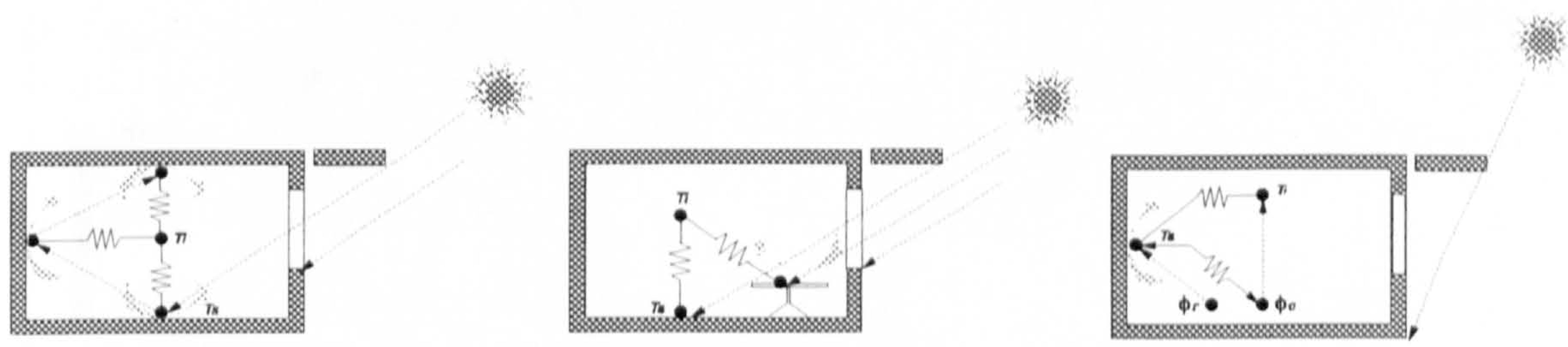


2.9 Effect of wall thickness on the reduction of heat and on the temperature of the internal surfaces for exposed south-facing walls. Data from field measurements in Seville.

2.4.5 Interior Thermal Coupling

If no heat is present in the room, there will be little difference between the temperatures of the internal surfaces and the air. This difference will be created only when heating or cooling of the air is introduced. If heat is radiated to the internal surfaces, there will be a process thermal exchange between them and these mechanisms will tend to reduce their temperature difference. As discussed in section 2.2, radiative exchanges of heat will not affect directly the temperature of the air but through contact with air, the surfaces will cause a temperature rise. The variations of air temperature will then be a consequence of the temperature variations in the surrounding surfaces.

In buildings with thick or well insulated structures on the outside, the internal surfaces will dominate the thermal conditions of the interior. The internal surfaces lose and gain heat according to variations of internal or external heat pulses. The internal air temperature then is determined by the temperature of the convected heat from the surrounding surfaces. As a result, a thermal network of nodes is produced within the room, 2.10. When the sun rays penetrate the room and reach an internal surface, some radiation will be reflected and some will be convected to the other surfaces, but after a series of heat exchanges between the surfaces, the larger proportion of heat will be absorbed and stored by the mass, (2.10a). The temperature of internal surfaces will not increase much and consequently, nor will the air's. The total room air temperature will increase considerably if incoming radiation is intercepted by furniture. In this situation, most of the radiation will be reflected due to the small thermal capacity of the furniture mass, and as the surface is heated up, heat will be convected to the air, raising the internal temperature of the room, 2.10-b.

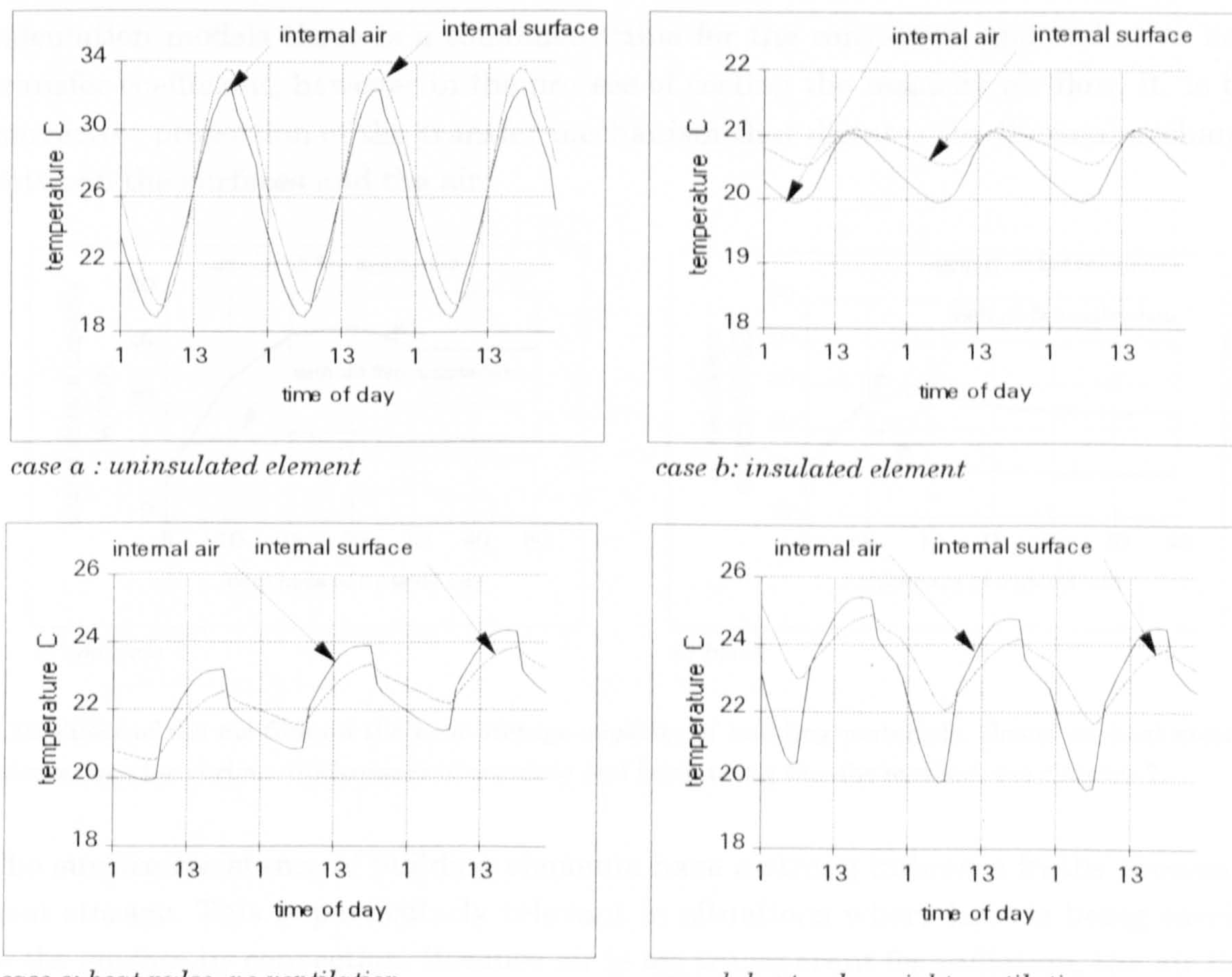


2.10 Thermal network created in the interior of a room between the surfaces and the air, as a result of internal or external heat excitations.

In the absence of solar radiation, the internal surfaces will be coupled with the radiative and convective part of the internal heat gain. The air will be warmed up by convective transfer both from the surfaces and the heat source, 2.10-c. To illustrate the interaction between internal surface and internal air temperature one can see four different situations. In the first situation, the internal surface temperature is affected by the heat flow by conduction from the external surface. This would be the case of an exposed, uninsulated and no so thick element, for example a 100 mm concrete wall. The picture in this case will be that the temperature of the air and surface will be very close. By the time heat has reached the internal surface, this will be close or even warmer than the air, and rather than absorbing, it will be releasing heat to the inside air, 2.11-a.

In the second condition the envelope has been protected (with a layer of thermal insulation on the outside), and the effect of the external surface temperature on the internal surface is negligible. Heat loss by conduction through the fabric will be restricted and it will occur mainly through glazed and other lightweight elements within the building. In the absence of heat in the room, there will be little variation throughout the day, the average air temperature will remain steady and a thermal balance is created between the indoor air and the internal surfaces, 2.11-b.

In the third condition, a heat impulse inside the room has been introduced. In this situation, the conditions at the wall surface will be a consequence of the internal heat gains. Heat will be absorbed and stored by the inner part of the wall throughout the day and will release some heat at night but in the absence of a heat sink for the wall mass, it becomes saturated and will be unable to absorb any more heat. The consequence of this would be that the mean air temperature of the room will tend to rise over the days and weeks (depending on the total time constant of the building, see section 3.4) until an eventual change in the outdoor climate breaks the course, 2.11-b.



case a : uninsulated element

case b: insulated element

case c: heat pulse, no ventilation

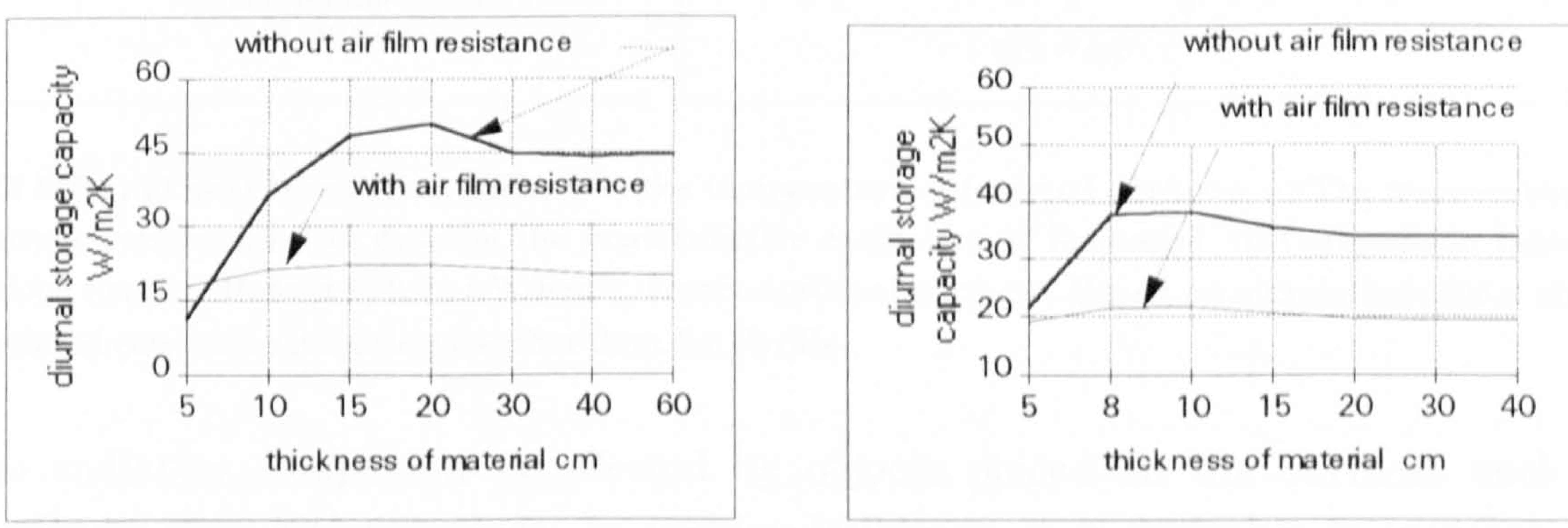
case d: heat pulse, night ventilation

2.11 Temperature variations of internal surfaces. Based on simulations for a single concrete cube using weather data for Seville.

Additional mass will not help heat dissipation even if the storage capacity of the walls augment and the internal heat will continue to build up. In the fourth case, night air is introduced into the room. As a result, the indoor air is replaced by cooler air and it will make contact with the surfaces promoting and accelerating the dissipation of heat. This will result not only in the reduction of the internal air temperature but as a consequence, it will help discharge the building mass during the night and prepare it for its role as the transitional heat sink for the next cycle. 2.11-d.

2.4.6 Effect of Air Film

The rate of heat transfer between building elements depends on the heat transfer coefficient of their surfaces. The radiative and convective heat transfer coefficient, is determined by the conductance/resistance of the air film that covers the surfaces of all elements. The heat transfer coefficient can be defined as the ratio between the convective proportion of the power density and the difference between the mean internal air temperature and the mean internal surface temperature. In most calculation models there is a combined value for the convective and radiative heat transfer coefficient, however in the process of cooling the mass by air flow, it is the convective proportion of the transfer mechanism that dictates the thermal exchange between the surfaces and the air.

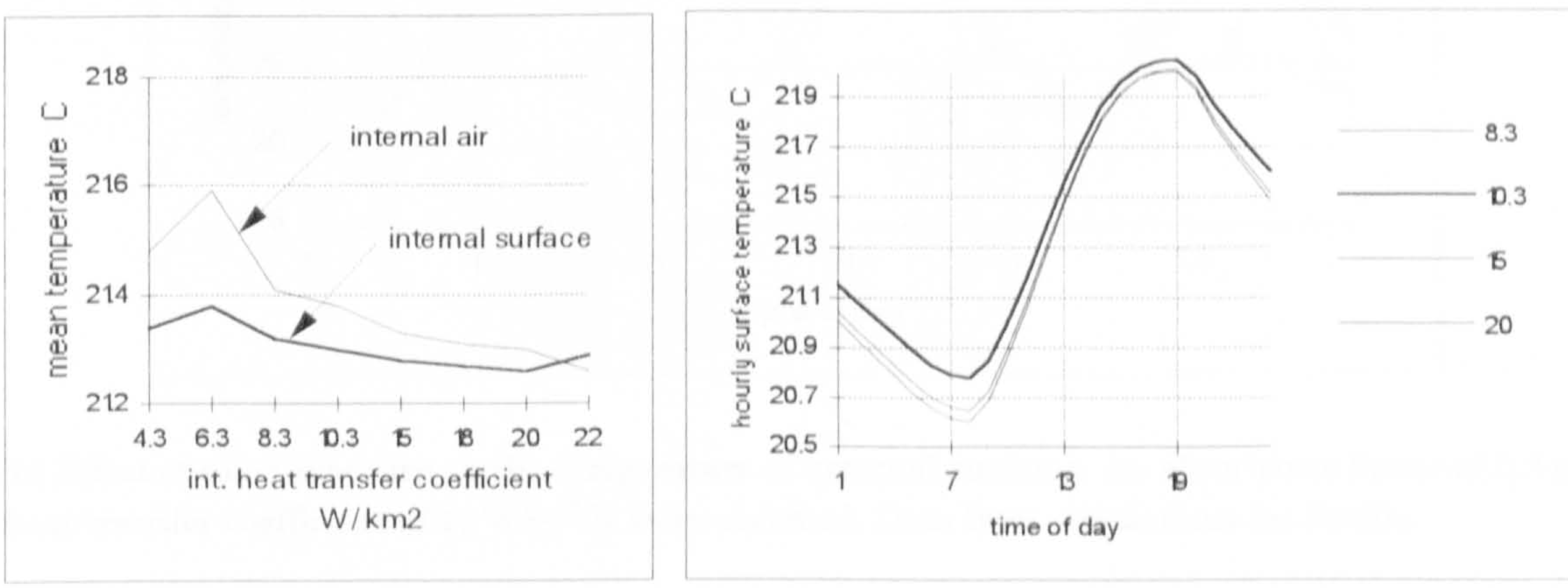


a) concrete *b) brick*

2.12 Effect of the air film on the heat storage capacity of building materials. Based on heat storage calculations for various thicknesses of concrete and brick using the dhc method, see chapter 7.

The surface resistance of building elements have a strong influence in the process of heat storage. This is particularly relevant in situations where heat is being carried to the surface by convection. Because air is too transparent for radiation, the air film close to the surfaces offers little resistance to direct radiation and a larger proportion of heat can be stored by a direct source (short-wave or infrared radiation). In convective situations, the amount of heat stored in a wall can be reduced by over 60% due to the effect of the surface resistance. The typical surface conductance of internal surfaces is around 8.3 W/m^{2}K of which $^2/_3$ is radiative and $^1/_3$ is convective. Graphs 2.12a and 2.12b, illustrate the extent to which the surface resistance can affect the amount of heat that will be stored in a element. The calculation of the effect of the air film on the heat storage is discussed in chapter 7.

The convective proportion of the heat transfer coefficient of surfaces can be increased by the effect of air being blown to the surface, for example with the use fans. Values of heat transfer coefficients of internal surfaces vary between 3.4 to 17 W/m^2 K, the higher numbers representing the value when ceiling fans are operated inside the room, [1]. This process known as forced convection is used to promote heat dissipation from the mass of the building at night.

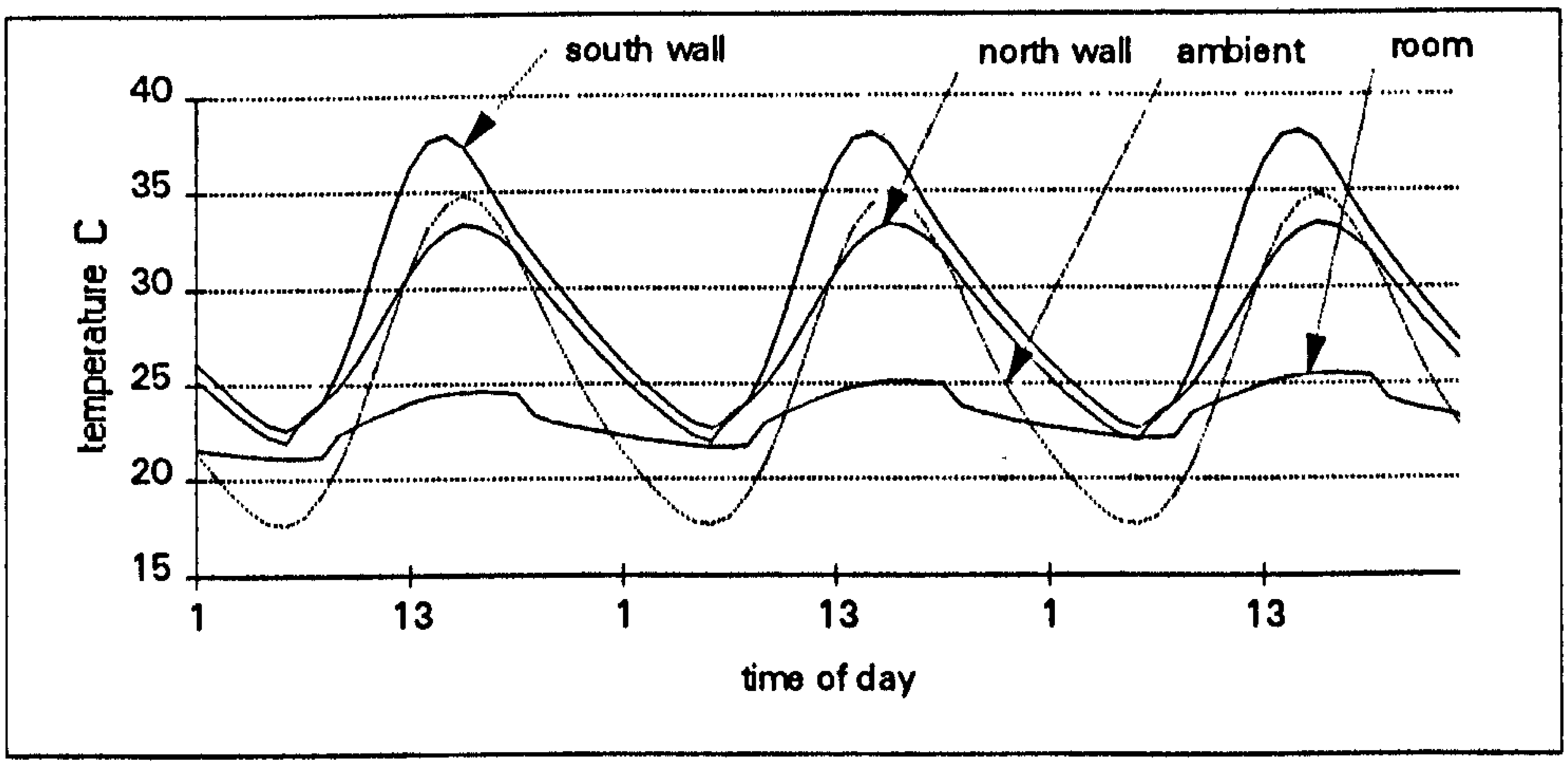


2.13 Effect of heat transfer coefficient on the temperature of internal surfaces. a) The temperature of internal surface tend to drop as the heat transfer coefficient is increased. b) Comparison between various heat coefficient values (W/Km^2), for the internal surfaces. Based on simulations for a single insulated concrete cube using weather data for Seville.

The radiative component is affected by objects placed on the surfaces such as furniture, rugs and paintings. In passive buildings, it is desirable to increase the heat transfer coefficient in order to enhance both, heat absorption during the day and dissipation at night. The extent to which ventilation affects the heat transfer coefficient should be a separate subject of research [52], [60], [61].

2.4.7 Effect of Surface Orientation

In hot conditions it is desirable to minimise the exposure of the envelope to the sun unless indoor heating is required later, usually the case in locations with large daily temperature fluctuations. As discussed in the previous section, the external surface may in some cases affect the internal temperature of buildings. The temperature of shaded external walls can be considerably lower than exposed surfaces. Shading can be provided to the walls, and in some cases to roofs, by vegetation or adjacent buildings. The colour and texture of external of walls and roofs can also influence their thermal conditions because they affect the absorbance and the heat transfer coefficient of their surfaces. As speed and direction of wind vary, the heat transfer coefficient of external surfaces will also depend on orientation. Rough surfaces have higher surface conductances than smooth surfaces and roofs have the higher conductive surfaces.

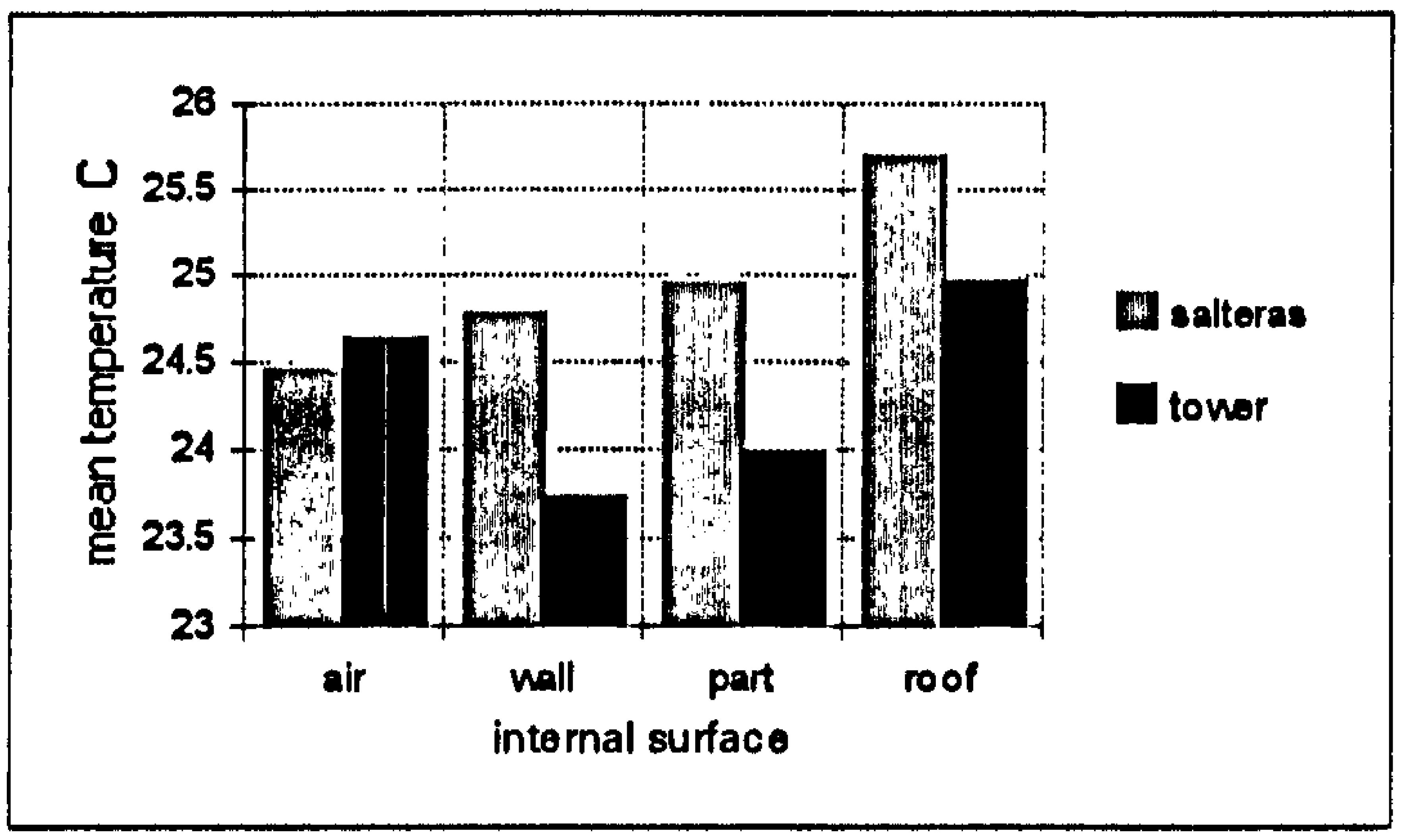


2.14 Effect of solar exposure on the temperature of external surfaces. An absorbance factor of 0.3 and a heat transfer coefficient of 12 W/m^2 K were assumed. Data from simulations for Seville.

2.5 Heat Distribution

The thermal exchange produced between surfaces after an impact of heat in a building tends to produce a balance on the temperature of the building mass throughout the space. When the envelope of a building is made of different wall construction types, i.e. with different thermal properties, the thermal characteristics at the surfaces may be different, however, the temperature difference between the them will increase their convective and radiative heat transfer and the tendency of these mechanisms after some time will be to even up the surface temperatures back again within the space. When an internal surface is exposed to direct radiation, the fraction of the wall in contact with the sun patch will be hotter for some time than the rest of the wall and the other surfaces, but again the general tendency in time will be that a thermal balance is found within the surfaces.

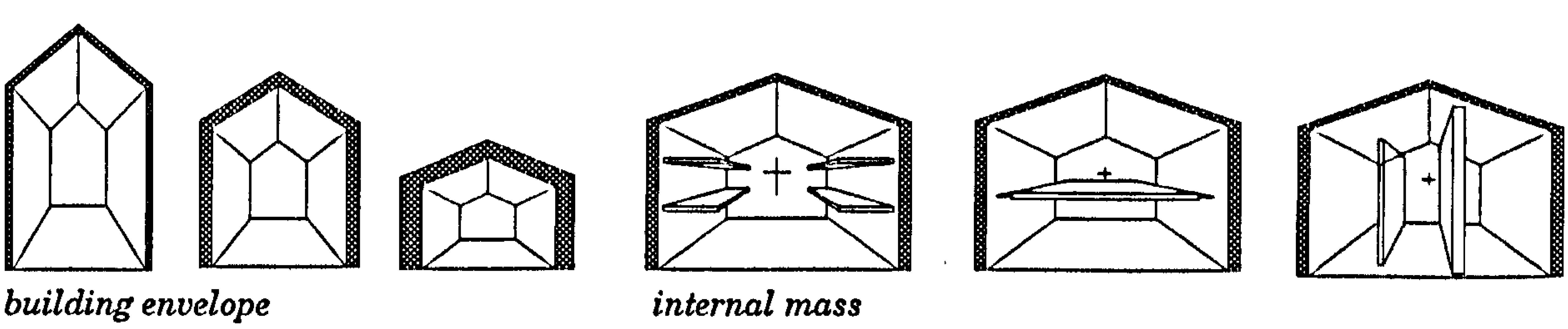
Another important factor influencing the distribution of heat within the room is the temperature stratification that gradually results from the forces of natural convection within a space. As air tends to rise along the warmer wall and descent along the coolest surface moved by the pressure distribution throughout the room, in reality, all the surfaces within the building will have a different temperature the ceiling being the hotter and the floor the cooler. Graph 2.15 shows the mean internal surface and mean internal air temperatures measured in two buildings in Spain, (see field experiments in chapter 5). The temperature at the ceiling surfaces tended to remain warmer than the rest while the internal partitions were the cooler. This was observed in the two buildings. Note however, that in one of the buildings, the mean internal air temperature is lower than the mean temperature of the building surfaces and in the other building the air temperature is higher. The temperature of the internal air can be higher or lower than the building mass according to the of magnitude and frequency of internal gains. The description of internal gains of these particular buildings is presented in chapter 5.



2.15 Mean internal surface and internal air temperatures of two buildings in Seville. Average values from 10-day measurements.

2.5.1 Area Geometry and Depth

The disposition of the building components throughout the building will determine the distribution of heat within the building mass. The area, the geometry, the thickness, the location, the colour etc., of elements are all aspects that influence heat storage and distribution in the building. The extent in which these variables affect storage and distribution of heat and the thermal implications inside the building is currently an area of research.



2.16 Different spatial configurations resulting from various forms of mass distribution within buildings of similar mass volume.

Thermal mass in buildings can be increased by adding depth to the walls and roofs and increasing their surface area. Internally, the overall mass of the building can also augment by the placement of internal massive elements, such as internal partitions, stairs, mezzanines, etc. In this respect, buildings with similar volume of mass (similar thermal capacitance) can have very different spatial configurations and may also have different thermal performance, 2.16. The most efficient distribution of thermal mass throughout the space, should be set as a main design target and should be determined according to the particular characteristics of the building type. Thick structures can store more heat over longer periods of time, for example for seasonal heat storage, but its diurnal effectiveness may be affected by long term storage. Thin walls store and release heat in a shorter period of time but may be affected by external excitations. The effect of thermal mass distribution on the internal climate of enclosures is discussed in the parametric studies in chapter 6.

2.6 Thermal Inertia and Ventilation Effects

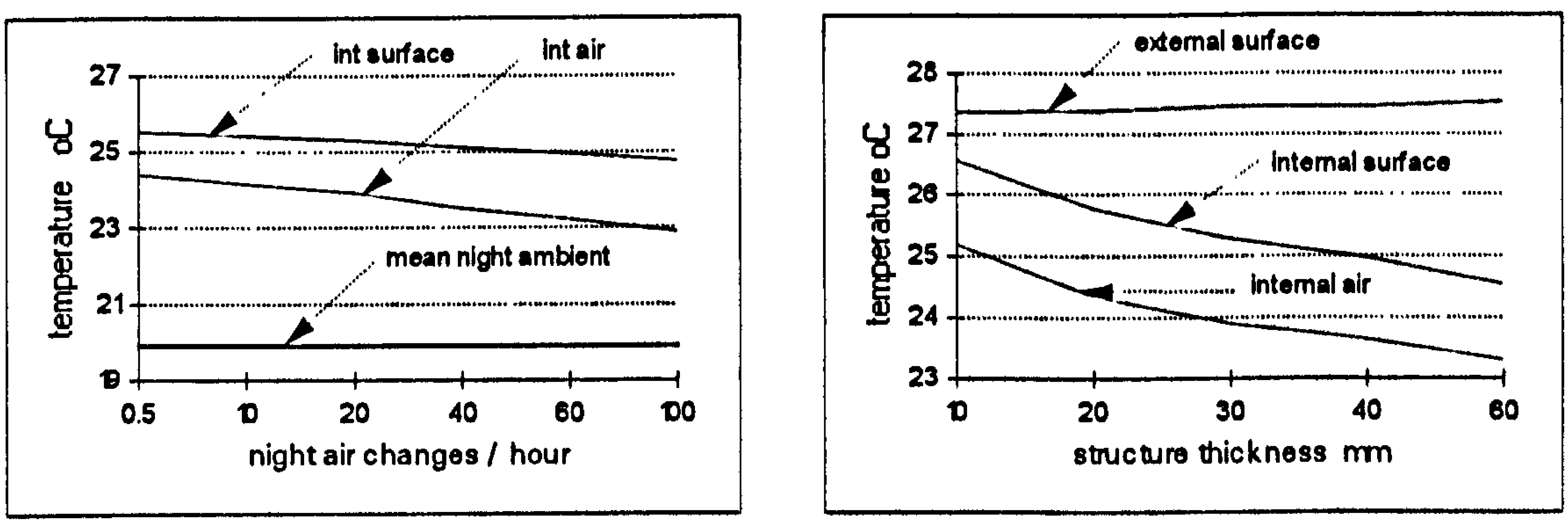
A minimum level of ventilation is required for the provision of fresh air and remove carbon dioxide, odours and excessive humidity. In warm or hot climate conditions, where the temperature outside is often above the internal air temperature, day-time ventilation should be restricted to the lowest possible rate. The minimum ventilation requirements will be determined by the number of occupants and the type of activity inside the rooms. When the outdoor temperature is similar or slightly lower than the internal temperature, natural ventilation can be used to encourage heat dissipation from the occupants by evaporation even if this does not produce a cooling effect of the building mass. The heat transfer coefficient of the skin is increased by the effect of the air making contact with it producing evaporative heat loss from the body. This process is known as physiological cooling and is most often used in conditions of high humidity.

2.6.1 Convective Cooling

The temperature difference between the building and the external air creates a series of different pressures around the building producing air motion. This convective process can be advantageous in situations of overheating when both the internal air and the building mass are at a higher temperature than the external air. The external air will then infiltrate the building interior and will reduce its temperature. In warm conditions this process known as convective cooling, usually occurs at night and the early hours of the morning. For a building that has been exposed to external and internal heat gains during the day and it has absorbed certain amount of heat, the night air will provide the heat sink to begin dissipation.

Depending on the extent of the temperature difference and wind speed, the tendency of the heat dissipation process will be to cool the structure down to the level of the outdoor air. This however, will be unlikely the case. The thermal inertia of solid elements make them store a proportion of heat which is always higher than what the air is able to carry, thus, even if ventilation is provided at high air velocities, massive surfaces will normally not drop below the outdoor temperature. An exception of this can be windows and other glazed elements in the envelope that have very small heat capacity. This is because in addition to ventilation, some very lightweight surfaces in the building envelope may lose further heat by radiation to the sky. In these cases the temperature of the surfaces can drop below ambient.

Internal surfaces can be cooled by the contact of night air. The extent of this cooling effect will vary according to the disposition of openings within the room. In most situations, when cooling by night ventilation is being provided the temperature of the air inside the building will be halfway between the internal surfaces and the outdoor air temperature.



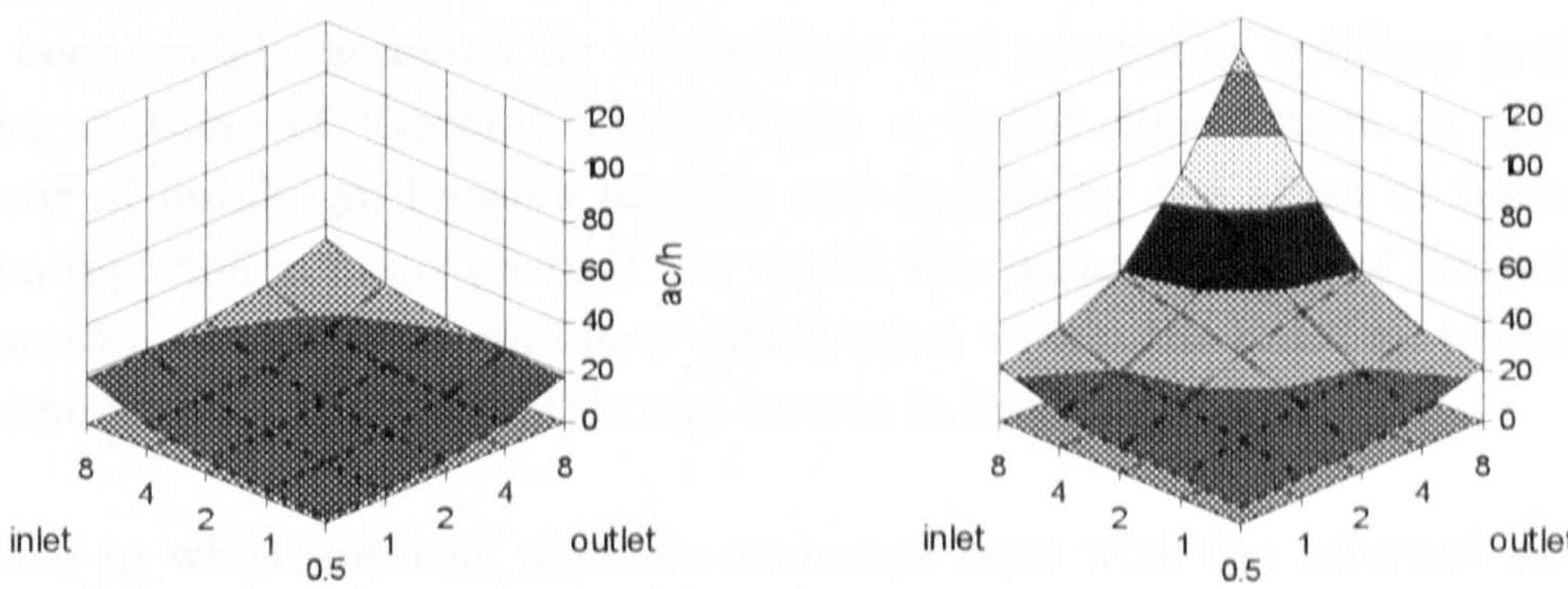
envelope structure : 30 mm *night air change rate : 20 AC/H*

2.17 Effect of night ventilation on the mean air and mean surface temperature inside a single concrete cube. The curves show the average daily temperature for each value of air change and structure thickness. Based on simulations using weather data for Seville.

The extent to which mean internal air temperatures can drop as a function of increased night ventilation is different from the rate at which the surface temperature decreases. The building structure will always retain some heat and will always take longer to cool down. The heavier the structure, the longer it will be to cool it down. A simple method to estimate the effect of night ventilation on internal temperatures by the means of increasing the heat transfer coefficient of internal surfaces is given in [1]. Reductions on day-time internal temperatures up to 8 K are reported there by increasing the internal night-time heat transfer coefficient from 3 to 17 W/m^2 K. Night convective cooling is reported to have a contribution of 25% of the total heat loss of an industrial building [25]. Night ventilation acts as a complementary component to the effect of thermal inertia in buildings. Lightweight structures do not benefit from night cooling because their heat storage capacity is small and because the interior is not sufficiently protected from solar radiation the internal temperatures would build up quickly and the cooling effect of the night before would be rapidly lost. In lightweight structures, the heat loss through the envelope increases and the effect of convective cooling is less emphasised. As the total capacity of the enclosure increases, the night cool air flowing inside makes gradually a more significant effect on the internal space. The external surface temperature however may increase with thickness as shown in graph 2.17-b. This is due to the higher heat storage capacity resulting from thicker walls.

2.6.2 Air Flow and Ventilation Rate

Wind speeds frequently drop at night-time causing a reduction on ventilation rates of a room. In the absence of wind, the pressure created by the temperature difference between the indoor and the outdoor air produces air to move inwards and ventilation is possible.



a) wind velocity: 0 m/sec *b) wind velocity 1 m/sec*

2.18 Air change rates for a single enclosure with different inlet and outlet area (m2) and two different wind speeds. Wind direction is assumed perpendicular to inlets. Based on simulations for a single room. Further air change values for other conditions of this room are given in Appendix 7.

The position and the orientation of inlets have a significant effect on the overall ventilation rate. The difference in openings height can help drive air movement in the absence of natural wind currents. Air tends flow into rooms through the lower openings and as the inside air becomes warmer, it leaves the space through the higher apertures due to the difference in pressures at different heights. This process is known as stack effect. A model for estimating night time ventilation by stack effect and a correlation with comfort assessments is proposed in [24]. The effect of outlet and inlet height difference on the air change rates for a single enclosure is given in Appendix 7.

The control over direction of air flow inside buildings can also be advantageous for night time cooling. With controllable air flow devices it is possible to divert day-time air flow from night time flow and direct the cooled night air directly to the building surfaces and if possible the inner structure as well. The incorporation of special vents to direct the flow into the voids within the structure have also been used.

Air change rate calculations present the difficulty of the intermittent nature of wind speed and direction. To facilitate the process, these are usually made from constant values. Graph 2.18 shows the potential air change rates achievable as a function of opening area. In conditions of constant wind speed the size of the openings will determine the rate of air changes per hour in a room, however the real possibilities for increasing opening area will have to be measured against concerns about privacy and security.

2.7 Conclusions

It has been widely accepted by researchers and practising building professionals that the systems of thermal inertia have a major significance in the thermal behaviour of buildings. Passive heating and cooling by the effect of thermal mass has been reported in many parts of the world. The understanding of the principles of heat transfer, heat storage and heat distribution within the building is essential for the optimum use of the effects thermal inertia in buildings.

The forms in which internal surfaces exchange heat with the internal air have an important effect on the thermal characteristics of rooms. These will vary according to the position, the characteristics of the surface and the contact with air movement. The orientation of external surfaces of some type of structures may have a considerable thermal effect on the internal spaces. The optimum distribution of heat is required to avoid long thermal storage when not required and to ensure night-time heat dissipation.

Night ventilation should be used as an intrinsic component within the strategy of thermal inertia of buildings. Maximum nocturnal air change rate can provide convective cooling for the air temperature and can promote heat dissipation from the building mass.

Design guidelines have been given for heat storage applications in cool and sunny winter locations to reduce the heating requirements in residential buildings [26], and for summer cooling by night ventilation [1], [66] and others. Design guidelines for the optimisation of thermal mass for buildings in warm climates is the main area of investigation of various researchers [16, 17 24, 60, 61, 63]. Quantification of thermal mass effects for specific building types and locations are required.

3

Analytical Parameters

3.1 Quantification of Heat Flow and Heat Storage

Background and Evolution

Research on the area of heat storage and periodic heat flow through building elements dates back to the 1930s when Houhten and others [34] first proposed a mathematical method to obtain the rates of heat flow through simple homogeneous materials based on experiments on test panels. They first made the now widely accepted analogy between heat flow and electricity flow (heat capacity-electric capacity and thermal resistance-electric resistance) and measured the delay effect of heat flow by some materials. Of the potential application of the results from that paper, Campbell [34] wrote: ".. by blowing cool air through a church during the night and keeping the building closed after sunrise, the temperature of the inner contents will be lowered considerably and they will absorb heat given off by the audiences during services until about noon. This will maintain a comfortable condition approximating that obtained by refrigeration.." Further work was later carried out by Alford, Ryan and Urban [35] who first introduced the concepts of *decrement factor* and *lag angle* [36], and by Mackey and Wright [37] introducing the concept of *sol-air-temperature and time lag.*

The *equivalent temperature differential* method was introduced by Stewart [39] who states that the density of heat flow through an element,

$$q = U * \Delta T \tag{1}$$

The *notional outdoor temperature* (Tno) was used in this method to account for the effect of solar radiation, the internal surface conductance, the decrement factor and the time lag. The *equivalent temperature differential* method, adopted for the ASHRAE Handbook of Fundamentals [25] was found to be adequate for everyday routine design work by Stephenson [40] , who later developed the *response factor method* which became widely used in America in the 1960s and 1970s.

The concept of decrement factor was further developed by Danter [41] defined as the *transmittance ratio* (U'/U) in combination with the time-lag concept. Based on this work, a method for calculating the thermal response of buildings was developed by Loudon and Danter [42] [43], in which the concept of *environmental temperature* was incorporated, leading to what today is known as the *admittance method.* Givoni [50a], developed a simplified method using a single time constant to describe the

See full Nomenclature at the end of this chapter, page 65.

heat storage capability of a building. The thermal time constant (TTTCB) was later extended by Givoni and Hoffman [50b] considering a heat sink in the internal mass of the building as a thermal condenser. As the interest for passive solar heating and cooling in buildings increased during the last two decades, a number of methods for the quantification of the effect of thermal inertia in buildings have been developed upon the basis of the time constant and admittance procedure [26], [44].

3.2 Heat Storage and the Admittance Method

The calculation of the thermal characteristics of buildings described within the admittance procedure includes four areas of analysis: energy transfer through the fabric, energy release within the building, energy storage in the structure and the effect of ventilation. The admittance method distinguishes two important characteristics; first, it defines the process of heat flow to and from the surfaces of materials over the 24-hour cycle of temperature variation, and second it defines the resultant temperature swing. The thermal admittance of a building element expresses numerically its ability to absorb or release heat when the surface and the air temperature are different. The admittance of a room or building can be defined as:

$$Yt = \Sigma (A * Y) \qquad (2)$$

The concept of thermal admittance is discussed by various authors [5], [45] as the ratio of heat flux variation to temperature variation ($2\ \Delta\Phi / \Delta Ti$) during a 24-hour cycle and can be expressed as:

$$Y = \sqrt{2\pi\ \lambda\rho c/P} \qquad (3)$$

3.2.1 The Admittance Algorithm

The development of the methods referred to in the previous section led to the definition of the heat flow rate as:

$$\Phi t = AU\,(T_{sol} - Ti) + AU\,dcr\,(T_{sol\,(t)} - tlg - T_{sol}) = \Phi + \Delta\Phi(t) \qquad (4)$$

The equation comprises two analytical areas which constitute the basis of the admittance method. The first part defines the average daily heat flow rate and the second defines the temperature swing at a particular time (t). The general assumption in this algorithm is that over a period of 24 hours, a diurnal cycle, the net heat flow due to temperature difference will be zero and that in the absence of heat gains in the building, the mean outdoor and indoor temperatures will be the same. The introduction of any form of heat gains will cause the internal temperature to rise at a level which, if thermal equilibrium is to be maintained, has to equal the ventilation and conduction heat loss. This balance can be expressed as:

$$\Phi s + \Phi i = (qv + qc) * (\Delta T) \qquad (5)$$

The total heat flow (Φ) during a diurnal cycle, at a particular time (t) can be estimated by the sum of the heat flow produced simultaneously by conduction heat gains through glass (A*U), the conduction heat gains through opaque elements (A * U * dcr), the ventilation gains (0.33 * N * V), the direct solar gains (A * asg) - for glass - and (A * U * dcr * abs * *fo)* - for opaque elements - and the internal gains (people and appliances).

The variations in heat flow will cause a variation in the internal temperature. If the variation is positive i.e. there is an increase of heat gains, part will be removed by ventilation or will be stored in the surrounding surfaces depending on their thermal admittance. The admittance method, introduces the concept of environmental temperature as a replacement for the internal air temperature because it correlates better with thermal sensation for the purpose of comfort analysis. The environmental temperature is defined as:

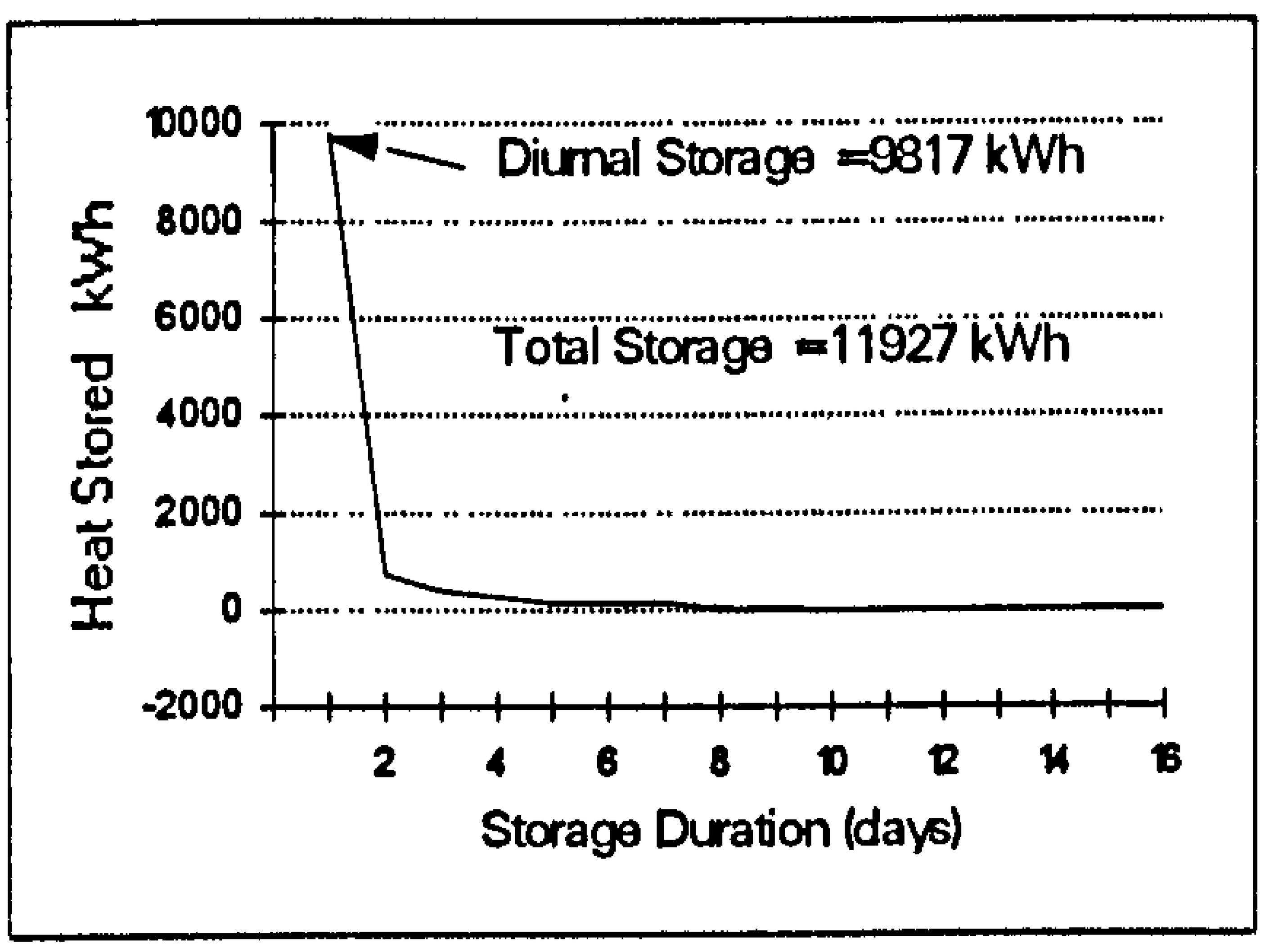
$$Te = (2/3)\, Tr + (1/3)\, Ta \qquad (6)$$

A modification to equation (4) is proposed in [38] to introduce the *dry resultant temperature,* the use of which is recommended for applications in cooler climates.

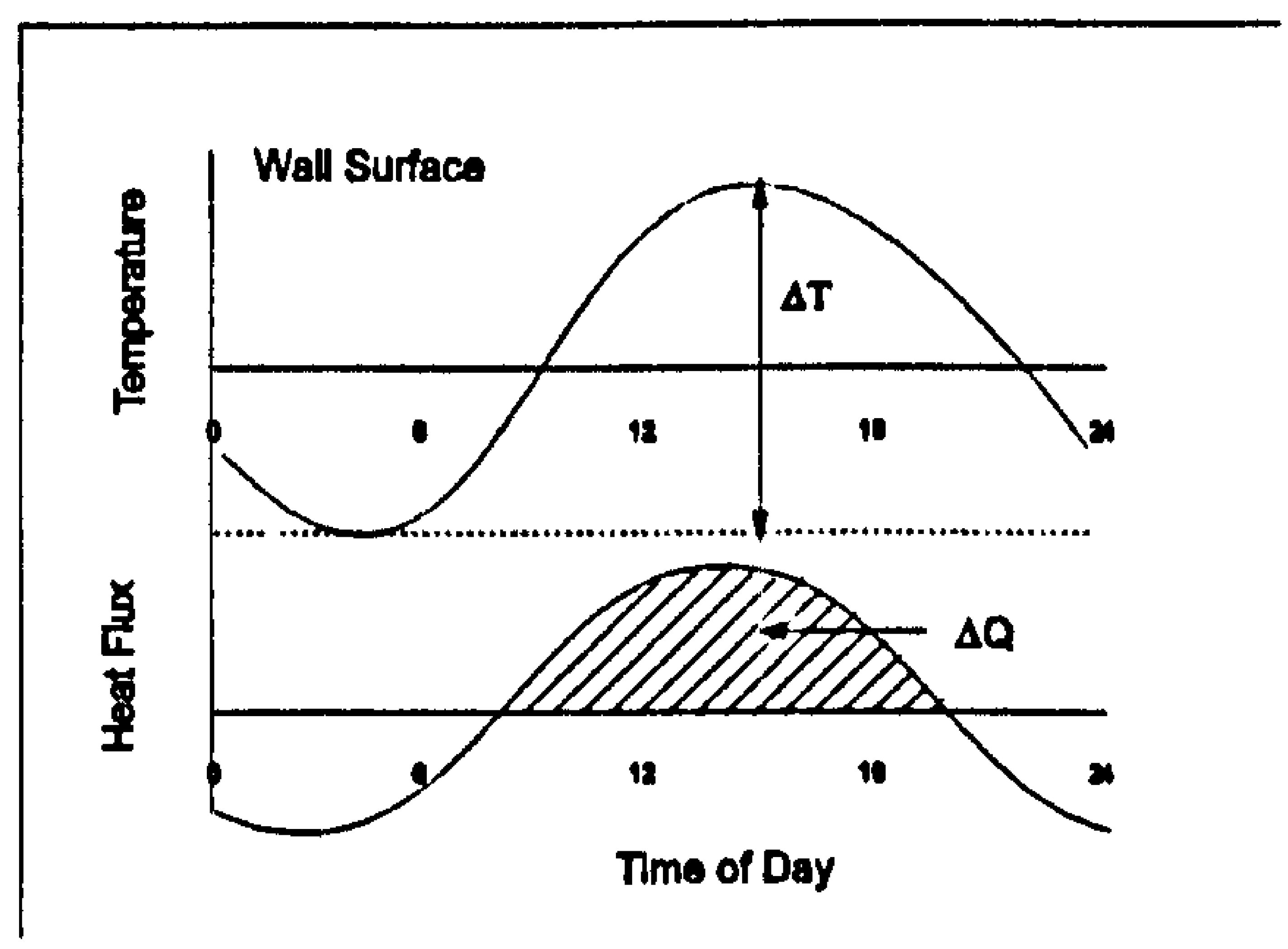
3.3 The Diurnal Heat Capacity

Based on the principles of the admittance method, the diurnal heat capacity *dhc* (5) allows the calculation of the internal temperature swing derived from the diurnal component of the process of heat storage-heat release in a room or building. The *dhc* parameter underlines the importance of the diurnal component of heat storage of a building in proportion to both, the short term heat storage (stored during a few hours) and the long term storage (stored for longer periods, days or weeks), 3.1a.

The concept of diurnal heat capacity relates two important aspects within the process of heat storage: the heat flow through the wall and the temperature variation at its surface. The diurnal heat capacity is the amount of heat that is stored per degree of temperature swing. This relation can be expressed as the ratio $\Delta\Phi/\Delta T$. 3.1b illustrates the thermal response of a thick wall to a heat input during a 24 hour cycle. The curves represent the diurnal component of the wall surface temperature and heat flow into the wall. The resultant surface temperature represented by the lower curve, follows the same wave of the heat flow curve but with a phase lag of 3 hours (45^0 phase shift) . The hatched area is the heat stored during half of the day. The same amount will be released during the next half.



a) storage duration



b) surface temperature and heat flow

3.1a Storage duration in the building during the winter season. The shape of the curve illustrates the dominance of the diurnal component of heat storage of the building in relation to the rest of the fractions. **3.1b** Surface temperature and heat flow for a thick wall under a sinusoidal heat input, from ref. [5].

3.3.1 From Thermal Admittance to Diurnal Heat capacity

According to the definition of admittance in equation (3), the performance of building elements for heat storage and heat release depends a great extent on the thermal effect of three properties: the density, the conductivity and the specific heat. Heat flows more quickly through materials with high conductivity which usually have a relatively high density. The relation of these three properties in building elements at a single angular frequency, $\omega = 2\pi/P$, are the basis for determining their diurnal heat capacity. The way in which the diurnal heat capacity relate to the admittance can be described with the following equations. The main assumption in the formulations is that heat flows in a one-dimensional form assuming a well insulated building envelope on the outside. The equations, with some variations in nomenclature are those by Balcomb [5].

from equation (3),

$$Y = \sqrt{2\pi\, \lambda\rho c/P}$$

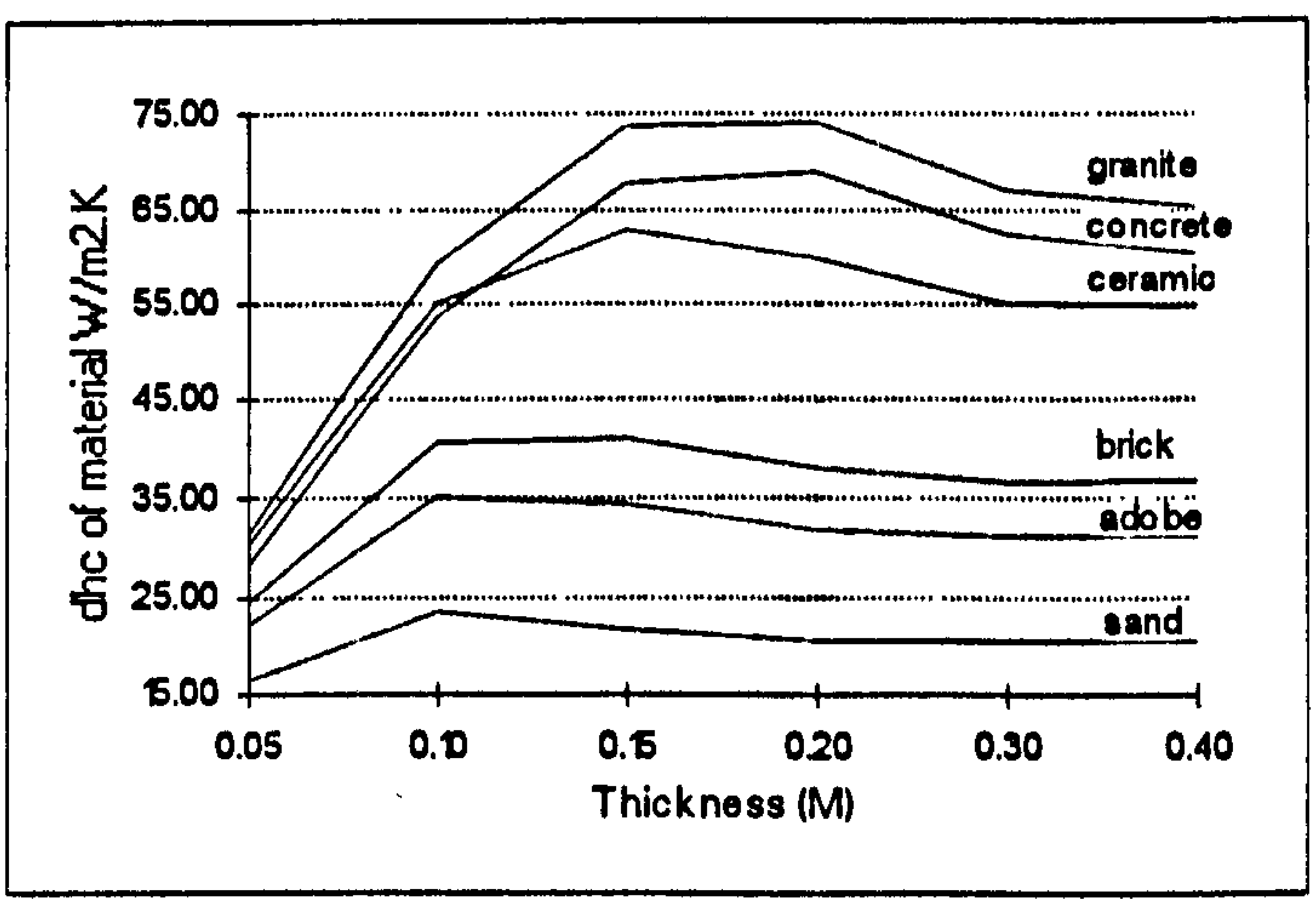
$$dhc = PY/2\pi \quad = 12Y/\pi \tag{7}$$

then, $dhc = 3.82\ Y$ and, (8)

$$dhc = \sqrt{P\lambda\rho c/2\pi} \tag{9}$$

3.3.2 Effect of Thickness on the *dhc* of Building Elements

With varied effectiveness between different materials, the diurnal heat capacity of building elements can be improved by increasing their thickness. This will increase their heat capacity and in turn their ability to store heat.



3.2 Effect of thickness on the diurnal heat capacity of various materials. Numerical values are given in table A5.2 in Appendix 5.

However, determining the limit thickness beyond which the diurnal cycle of storage is disrupted by the effect of excess storage, should be a main design target. This is called the optimum thickness X_o. and is derived as follows. The harmonic penetration depth, δ, of the building element is given by:

$$\delta = \sqrt{YP/\pi} \tag{10}$$

The ratio of the thickness of the layer and the penetration depth denoted in [5] as the dimensionless thickness, can be written as:

$$\xi = x \ / \sqrt{P\lambda/\pi\rho c} \tag{11}$$

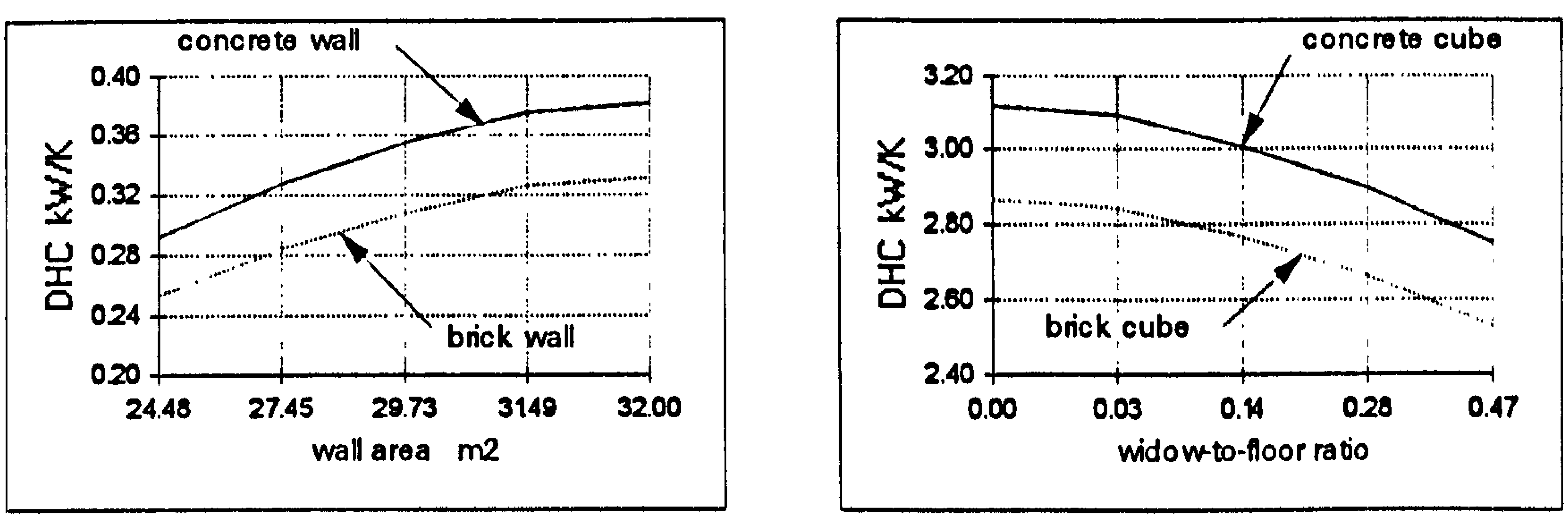
and the optimum thickness for a wall for a diurnal heat storage will be given by:

$$x_o = 1.18 \quad \sqrt{P\lambda/\rho c\pi} \qquad (12)$$

The constant 1.18 corresponds to an optimum penetration depth. Walls or roofs thicker than their optimum value (x_o) can cause a deviation to the cycle of heat storage- heat release and will be less effective for internal temperature reduction in spite of their higher thermal capacity.

3.3.3 Effect of Surface Area on the *dhc* of Elements

The process of heat absorption and release into and from building elements is optimised by the increased exposure of surfaces. While thickness will have a defined limit of effectiveness in the diurnal cycle, the increase of the heat-exchanging surface area will be beneficial. The diurnal heat capacity of walls and roofs can be increased with additional surface area.



3.3 **Total room diurnal heat capacity as a function of area of internal surfaces. The graph on the right shows the reduction of wall area by increment of window size. Based on *dhc* calculations for a single wall.**

3.3.4 Total *dhc* of a Room (*DHC*)

The *dhc* value is given in energy units per unit of surface area and it is measured in W/m^2 K. Analogous to the U value used under steady state conditions, the *dhc* of an element can be multiplied by the area of the surface to obtain the total value for that element. The process can be repeated for the rest of the elements of the room and the building. The overall diurnal heat capacity of the building *DHC* can be obtained by aggregating the effect of all the surfaces acting together. This will be the result of the vector sum of all *dhc* values that enclose the room. In this manner, a target *DHC* of a room or a building during the design process can be defined for a desired internal temperature swing.

3.3.5 *dhc* and Internal Temperature Swings

The main objective of the *dhc* method is to use the total *DHC* value to predict the temperature swing of the room, sTi. Once the *dhc* for all the elements of the room or building have been estimated, and the *DHC* is known, the temperature swing (ΔTr) can be calculated as a function of the direct gains of the building. Because the *DHC* is the amount of heat stored per degree of room temperature swing, the temperature swing can be obtained by dividing the amount of heat stored in the building by the *DHC*. In situations of direct solar gain, the amount of heat stored in the building will be a function of the solar penetration per square meter of glazing area, the total glazing area and the heat loss coefficient of the building.

This relation is given by the expression:

$$\Delta Ti\ (swing) = \frac{\Phi s - (Ti - To)\ hlc/2 + \Phi i/2}{DHC} \qquad (13)$$

The term daily means that the heat balance is calculated over the 12 hour period (from 6:00 to 18:00) The value from this equation is the 24-hour sinusoidal temperature swing of the room. A correction factor can be used for higher harmonics.

The equation for this is:

$$\Delta Ti = 0.61\ \Phi s\ /\ DHC \qquad (14)$$

Φs is the amount of direct solar gain per square meter of direct gain glazing area times the glazing area. The daily transmitted solar gains values for vertical glazing elements for various latitudes are given in [26]. If a target temperature swing is defined according to comfort requirements, the necessary *DHC* can be estimated.

3.3.6 Thermal Coupling of Elements and *dhc* Types

The calculation of the diurnal heat capacity for optimum heat storage requires a clear distinction between type of the thermal coupling building elements. This distinction will define the form in which the diurnal heat capacity will be calculated for each element. The building surfaces of a room will be thermally coupled between themselves and with the direct heat source. This coupling may be present in a radiative or a convective form. According to the thermal coupling type, the surfaces of a room or building can be grouped into three main categories:

In sunny winter conditions, all other surfaces including surfaces of closed-off rooms, covered floors and covered surfaces will be considered thermally remote and their *dhc* value would be 0. This is because the amount of heat that can be stored in this type of surfaces for later use in the day is minimum compared to direct gain surfaces and their contribution to space heating is negligible. However in situations of hot weather, surfaces within the indirect category can be very important. A general classification of surfaces according to their thermal coupling is shown in table 3.1.

Table 3.1
Thermal Coupling of Building Elements

Mass Element	Thermal Coupling	*dhc* Type
1 Surfaces in the direct sun	radiative	direct . *fa* *
2 Surfaces within view of the direct gain surface	radiative	direct
3 Surfaces of adjacent rooms to a direct gain room	convective	indirect

* enhancement factor. See *dhc* application and a more detailed surface classification in chapter 7.

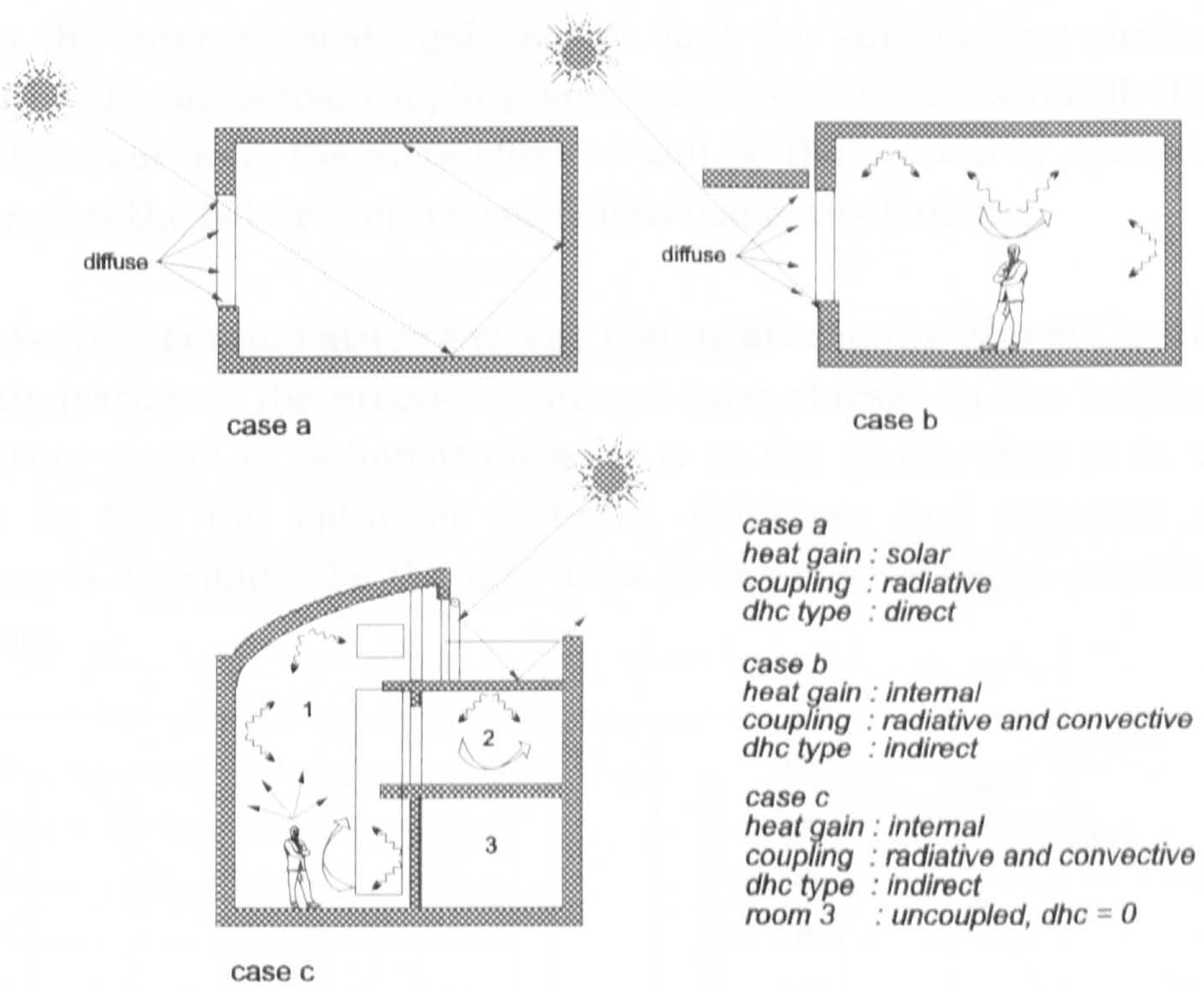
3.3.7 Application of *dhc* calculations for Warm Conditions

It has been stated [6] that the optimisation of thermal mass as cooling strategy, should begin when all measures to minimise heat gains have been taken (shading, thermal insulation etc.). As part of these measures, internal surfaces should not be exposed directly to the sun or thermally coupled with a direct gain surface. This is to say that a major interest in such situations would be to minimise the surfaces within categories 1 and 2 in the table 3.1.

However, an optimum *dhc* of the building surfaces should remain a main design target also in overheating conditions. The diurnal heat capacity of these surfaces will indicate their optimum thermal mass condition for a diurnal heat storage and release. This will ensure that the excess heat that is stored in the structure of the building during the day can be released at night. Higher *dhc* values than the optimum, for example by the addition of unnecessary thickness will store a larger amount of heat than it can release during a 24-hour cycle and the structure will be less capable of storing heat the following morning with the new thermal cycle. In many cases these elements will have a section in the centre where heat absorbed during one day will not penetrate. The heat deposited in that part of the wall may have penetrated days or weeks earlier and it may start flowing outwards at the time new heat is flowing inwards. This situation would reduce the overall heat storage performance of the room both in the heating and the cooling season.

3.3.8 Thermal Coupling In Overheating Conditions

Most surfaces within buildings under hot conditions should be away from direct radiation. If some direct radiation is allow through openings to an internal surface, these surfaces should at least be in thermally remote locations with respect to the main living areas.



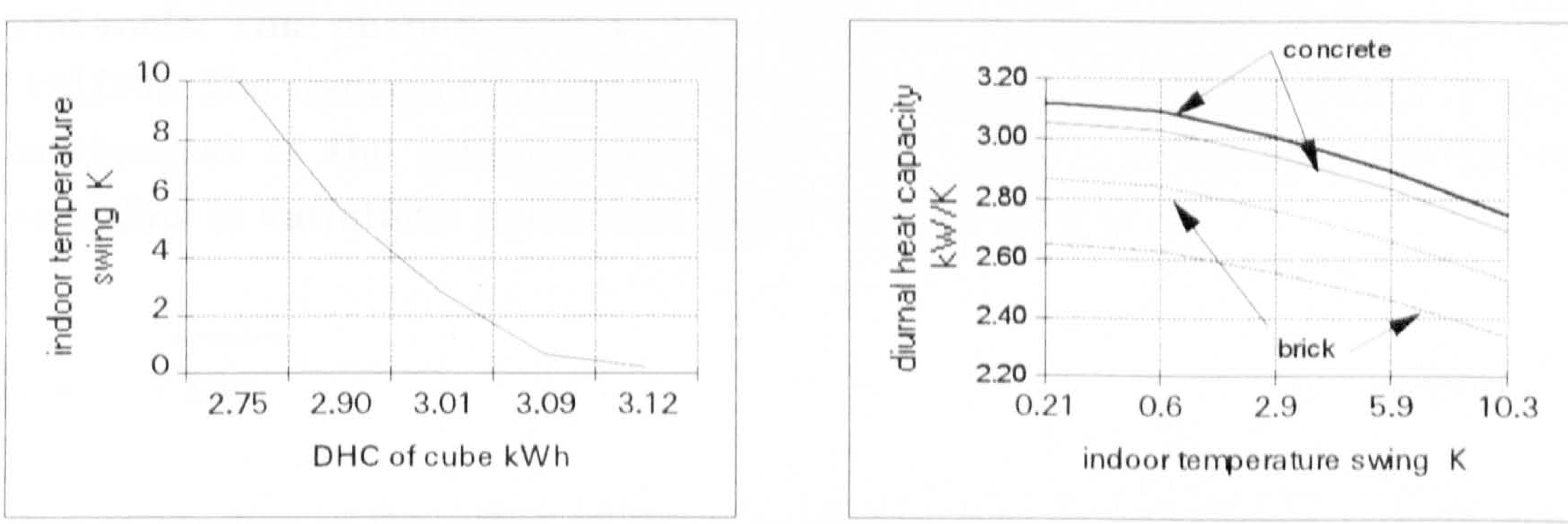
3.4 Thermal coupling types between heat source and the internal surfaces of the room. Case A shows the case of a predominantly radiative the coupling in a direct gain situation. In case B the thermal coupling is both radiative and convective but from an internal heat source and case C shows the cases where surfaces located remote locations like in closed-off rooms, are thermally uncoupled.

This will ensure the radiative component of heat exchange (direct type) is minimised and that there is a predominant convective (indirect) coupling between the direct heat source and the air node. In conditions of overheating, even if solar gains are minimised there still will be other sources of heat part of which will be absorbed by the surrounding surfaces depending on their admittance. The process of heat dissipation from internal sources will occur by radiation and convection with an additional proportion to be lost by evaporation from occupants. This can be expressed as ($\Phi = \Phi_{rad} + \Phi_{ev} + \Phi_{conv}$). The evaporative component will increase the air humidity but not its temperature. Because absorbtion of radiation by air is neglegible, the radiative heat component will not cause a rise in the air temperature but this will be deposited in the room's mass. The convective heat component will affect both the air and the mass temperatures.

As in the case of a radiative coupled direct (solar) heat gain, the heat exchange mechanisms between the surfaces and the room air will apply according to a temperature differential and the thermal properties of the elements. The difference in this case, will be that the main heat source would be the room internal gains. This suggests that for *dhc* calculations in warm climates a fourth type of coupling should be added to the three categories specified in table 4.1, namely the thermal coupling between the internal heat gain source and the surrounding surfaces. This is a predominantly concective coupling and a indirect *dhc* is assumed. The higher the *dhc* of these surfaces, the more effective will be the process of diurnal heat storage and therefore the better thermal conditions inside the building.

3.3.9 Internal Temperature Swings Calculations for Warm Conditions

The optimisation of the process of diurnal heat storage in the building during the overheating period is as important as it is in the winter thus is in the designer's interest to find the optimum material, thickness and exposure of walls and partitions to distribute the thermal mass in the most efficient possible way in both conditions.



3.5 Effect of the total diurnal heat capacity of a room on its internal temperature swings. Based on *dhc* calculations for a single concrete and brick cube for various thickness.

If all measures are successfully taken to reduce solar gains in a building, the surfaces with a indirect thermal coupling will be the predominant type. The prevailing source of heat in these cases, rather than the sun, will come from occupants, lighting and equipment or/and by ventilation when the outdoor temperature is higher than the indoors. The *dhc* is an integrated value for the thermal properties of surfaces as a function of the heat flow into the wall and its surface temperature swing in a diurnal cycle. The *dhc* for remote surfaces in conditions of direct solar gain was considered to be zero because their contribution to the room heating at night is negligible.

For rooms where direct solar radiation is excluded, a modified version of equation (14) has to be used. If the solar gains are replaced by the internal gains plus the day-time gains through the envelope, plus ventilation gains, (hlc) in equation (14), the temperature swing of the room can be estimated with the following equation,

$$\Delta Ti = 0.61\,[\Phi i + (hlc * \Delta T)]\,/\,DHC \tag{15}$$

For buildings with no auxiliary heating the equation can be simplified as:

$$\Delta Ti = 0.61 * \Phi t\ /\,DHC \tag{16}$$

where,

Φt = the daily total heat gain of the room (kWh)

3.4 The Thermal Effusivity

The form and speed in which heat is stored into and released from a building element as a result of an impulse of internal gain, depends a great deal on the properties of the materials closer to the heat source, for example the finishes of walls and roofs. This phenomenon is well expressed in the concept of thermal effusivity [16],[24]. The thermal effusivity b, is concerned with the thermal reaction of the first centimetres of the internal walls and their effect on the internal temperature according to variations in the heat gains. It is defined as

$$b = \sqrt{\lambda \rho c} \tag{17}$$

Recent studies of the effect of thermal inertia of buildings [47], have described the thermal response of a room or a building as a function of three physical aspects: the time constant, the thermal conditions of the wall (the envelope's ability to attenuate and delay its temperature) and the internal gain. A fourth component is the effect of night ventilation and can be studied separately.

3.4.1 The Time Constant of the Building

The product of the thermal mass of a wall or roof, defined by its thermal capacitance and the thermal resistance, defined by the surface area, will determine the time constant of a building, τ = RC. This is the time taken by a layer of a building element to increase its temperature as a result of variations in the external temperature. The time constant of a layer is the ratio Φ/U and the total time constant for a wall can be obtained by the addition of the time constant of each layer, $\Phi/U = \Phi 1/U1 + \Phi 2/U2 + \Phi n/Un$. The time constant will determine the thermal reaction of the building in time over one or several days or weeks as a function of its total mass. The time constant of the building envelope can be defined by the product RC. An enhancement factor (Me, Ce) can then be added to account for the internal mass and the ventilation conductance. The total time constant of a building can be expressed by:

$$\tau_{(total)} = RC_{(env)} * Me / Ce$$

3.4.2 Thermal Conditions of Walls

The physical characteristics that determine the thermal conditions of a building element over a period of time are the penetration depth, the attenuation factor and the time delay. The penetration depth can be defined as:

$$\delta = \sqrt{(\lambda P)} / \sqrt{\pi \rho c} = \sqrt{(dT/\pi)} \qquad (18)$$

The attenuation factor is given by:

$$Af = 2.72^{x/\delta} \qquad (19)$$

where x = wall thickness and 2.72 is a constant logarithm exponential. The time delay is defined as:

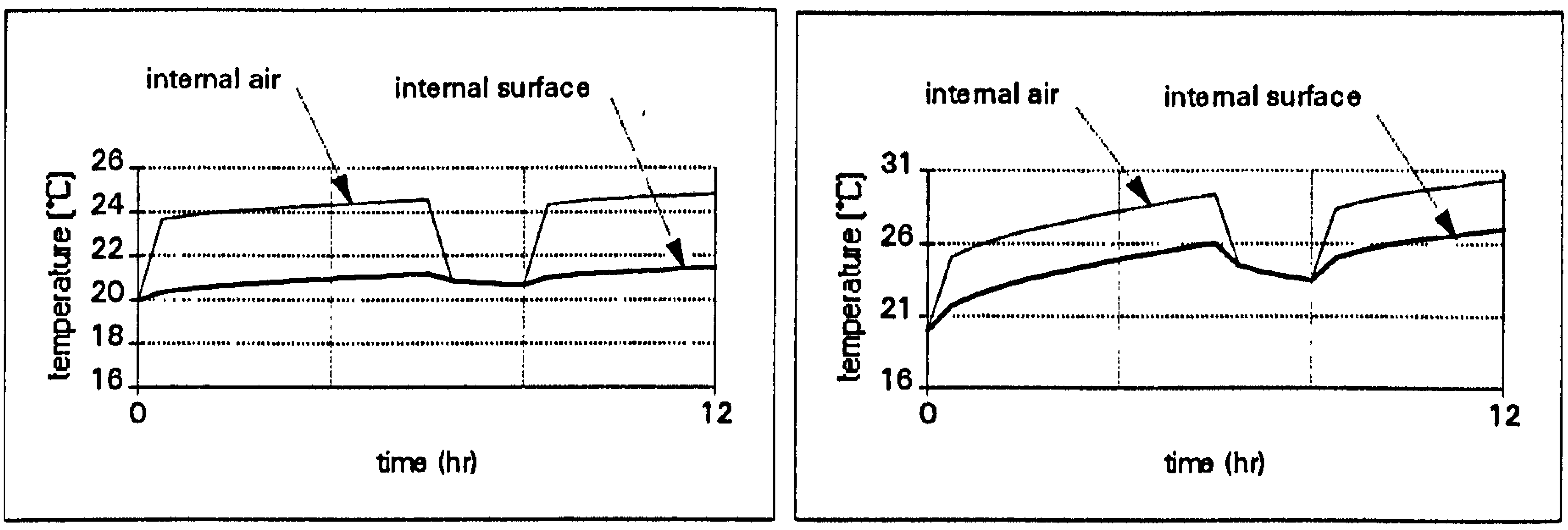
$$tlg = x/\delta * p/2\pi \qquad (20)$$

3.4.3 The Internal Heat Gain

The thermal effusivity model identifies two aspects which are relevant to the effect of internal gains inside a room. One is the rate of the heat pulse itself given by the heat flow density q. Internal gains, unlike solar gains, have of a non-periodical nature and will frequently vary in quantity and time of duration. The second is the characteristics of the internal surfaces of the room. These are determined by the internal convective heat transfer coefficient and the internal mean wall effusivity.

3.4.4 Internal Surface Temperature

The rate of internal heat gains of the room whether these are positive (heating by day-time ventilation) or negative, (cooling by night-time ventilation), will have a direct effect on the temperature of the internal surfaces. In turn, the surface temperature will determine the temperature of the room. The variation of surface temperatures is a function of the power density (q), the ratio between heat gain and the exposed surface area, $q = Qi / A$ and the mean dynamic thermal property of the exposed material, given by (b) thermal effusivity where, $b = \sqrt{\lambda \rho c}$.



wall A, b value = 2745 *wall B, b value = 549*

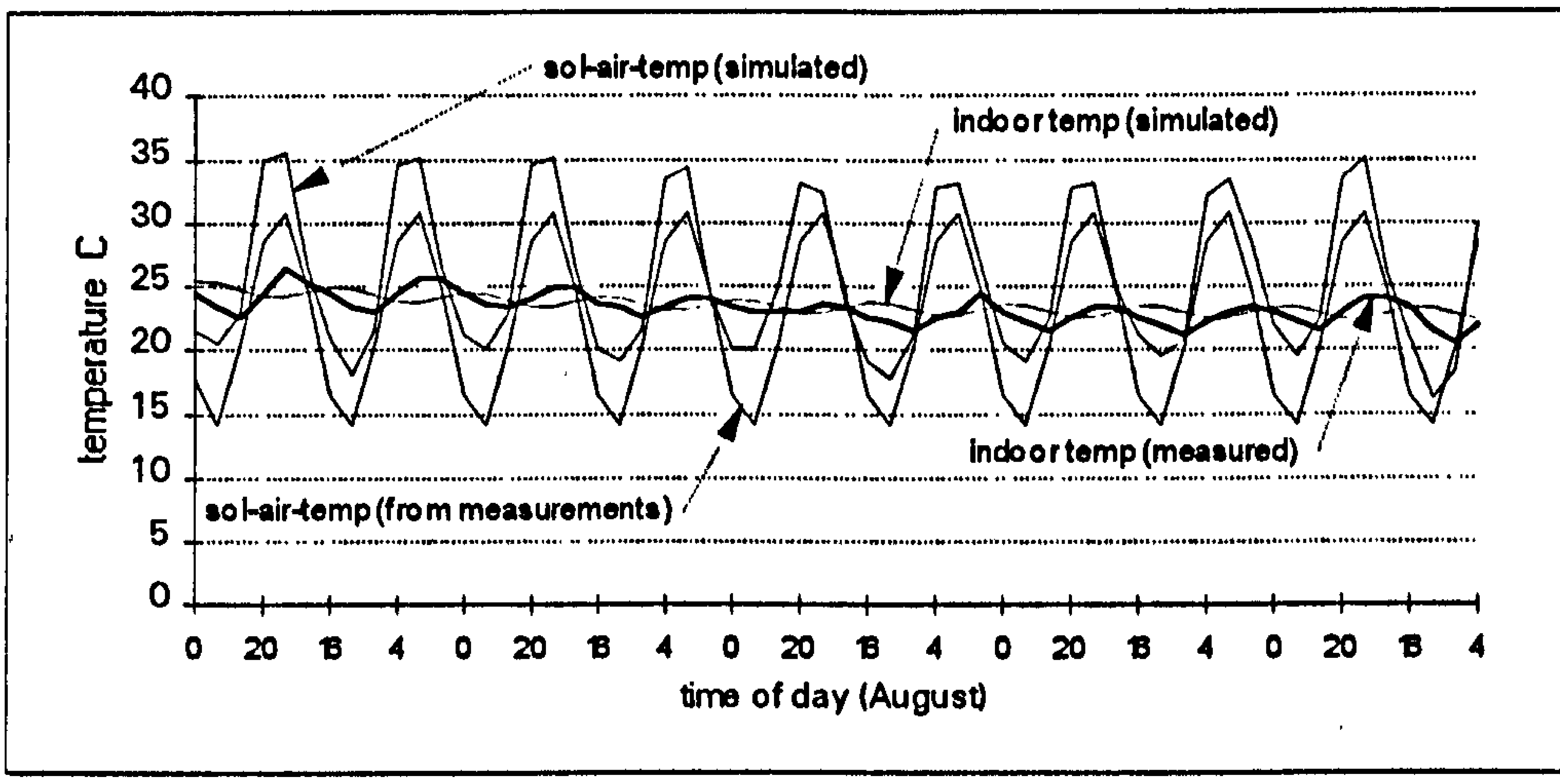
3.6 Internal air and internal wall surface temperature for two different wall effusivity conditions. Based on simulations for a single cube using the Leso-TMS model [47].

The difference between the wall surface and the air temperature of the room will depend on the convective part of the power density q_{conv} and the convective heat transfer coefficient of the wall (h_c). This can be expressed as follows:

$$T_a = T_s + q_{conv} / h_c \qquad (21)$$

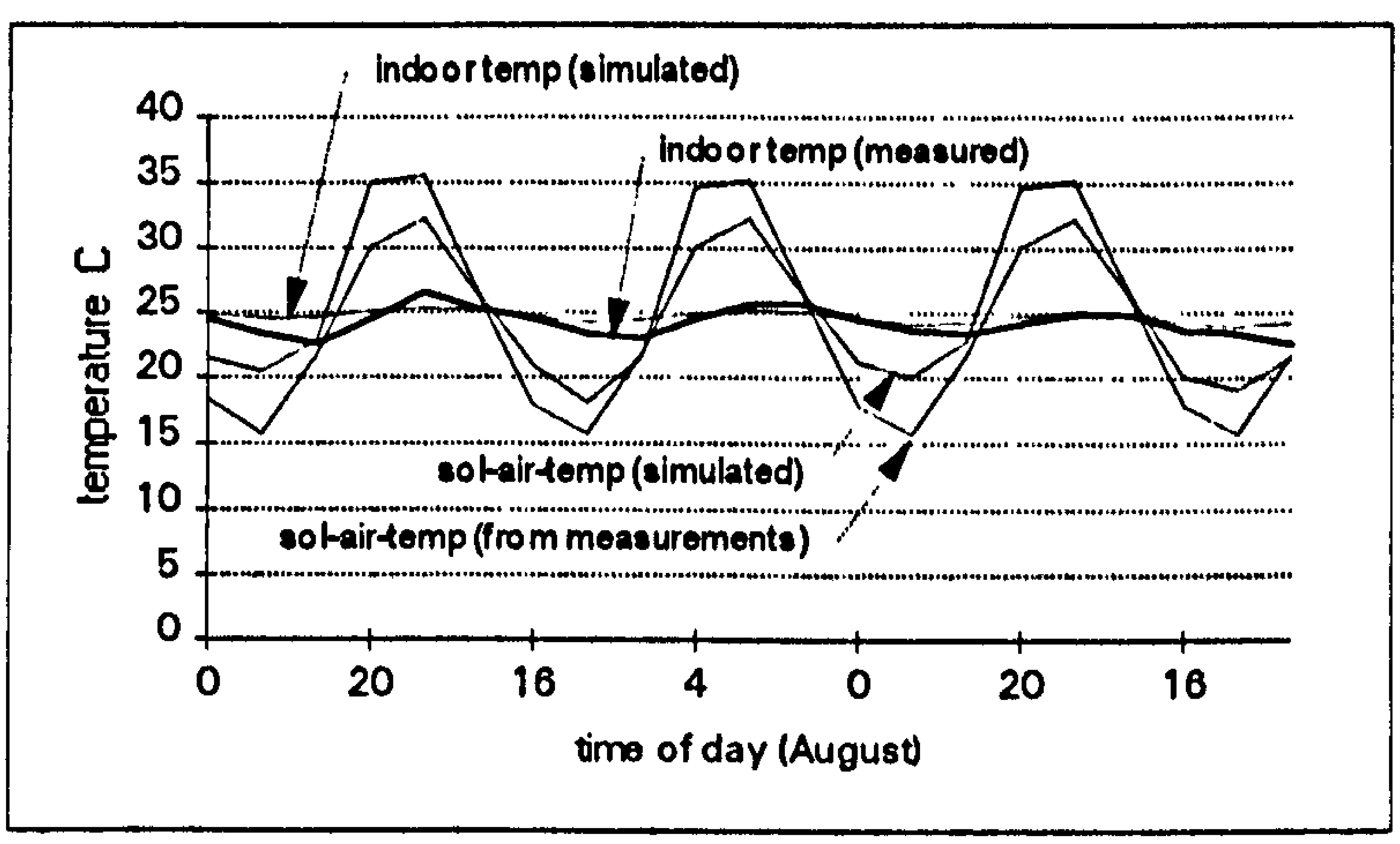
The effect of the thermal effusivity of two different surfaces is illustrated in 3.6. Cube A is made of a very heavy rock structure and cube B is made of lightweight brick walls. In both cases the room is subject to an intermittent internal heat gain rate of 2 kW, from 0 to 12 hrs, with a pause between hrs. 6 to 8. The heavier structure produces a smaller steep on the internal surface curve and a smaller temperature difference with the air temperature.

A comparison was made between the simulated and measured temperatures for a temporary residential building in Seville, Spain using the Pre-TMS [47] spreadsheet over a period of 10 days (3.7).



3.7 Comparison between measured and simulated temperatures for a residential building in Seville using the preTMS spreadsheet.

Further runs carried out in this and other monitored buildings in Seville (see chapter 5), showed a good correlation with respect to the internal swing and the mean indoor temperature. However, observing the results individually for each day, a large dephasing time shift between the simulated and the measured temperature curves was apparent in several runs, 3.7.



3.8 Measured and simulated temperatures for Salteras using the Pre-TMS spreadsheet. The corresponding time delay computed according to the total mass of the building was modified from 10 to 3 hours.

This time shift results from the total time constant calculations of the whole building. A smaller time constant would reduce the effect of this time displacement (3.8), and because the temperature swing correlation between the two curves is good, the general approximation of the whole simulation would be very close. It needs to be added that the values for the building data used in the Pre-TMS spreadsheet are average and no detailed description of the constructional characteristics of the structure is given.

3.4.5 Relation Between Thermal Effusivity and Diurnal Heat Capacity

The principles of the two models are centred on the thermal mass measure derived from the product of the density the conductivity and the specific heat of elements and surfaces. The thermal effusivity is developed within the structure of the European Norm where the definition:

$\lambda/\delta = \sqrt{(\lambda\pi\rho c/P)}$, except for a factor 2 is equal to the admittance term (Y) equation (3) in the diurnal heat capacity.

This in turn is equal to write: $b\sqrt{\pi/T}$ where b, is the thermal effusivity. The diurnal heat capacity is equal to the areal thermal capacity described in the Norm as $\chi = Y/\omega$ for a period P = 24 hours.

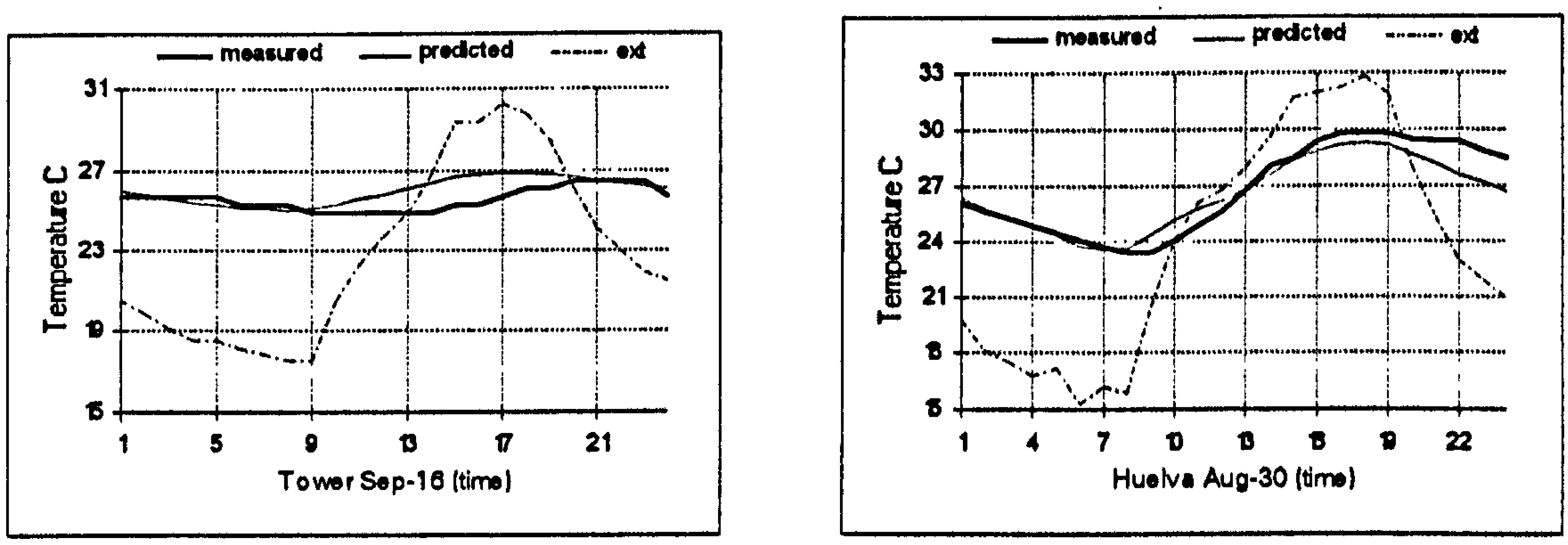
Then, the relation between the concepts of *dhc* and b can be found by the definition of equation (3) of Y defined within diurnal heat capacity as:

$\sqrt{(2\pi\rho c/P)} = b/\sqrt{\omega}$ then,

$$dhc = b\omega^{3/2} \tag{22}$$

3.5 Dynamic Simulation Tools

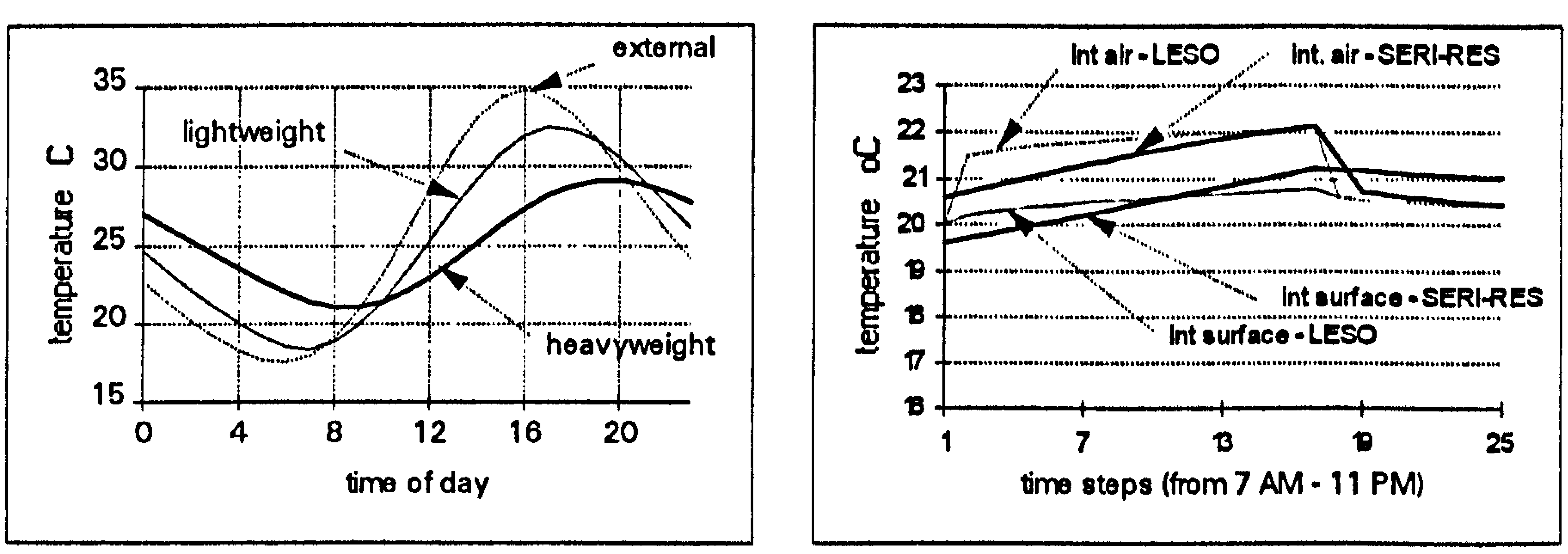
There is a wide range of thermal models able to take into account the characteristics of the building mass in order to predict internal temperature of buildings using different methods with different type of assumptions and levels of accuracy. The thermal model Quick, based on the development by Mathews and others [31], can be used for predicting internal temperatures of single-zoned buildings. A capacitor incorporated into the thermal network of the model is used as a mechanism to account for the heat contributions from the exposed envelope and the internal mass elements. This allows the prediction of the effective heat capacity of the structure and in turn, the effect of the diurnal heat storage in the building. The procedure to estimate the capacitor is given in [48] and [49]. The model was used for comparison with the internal temperature collected from real buildings using hourly measured external temperature. The results showed a very good approximation particularly in the lightweight building. The effect of a heavy structure was less accurately simulated especially with regard to the time lag, despite a close correlation in the temperature swing.



a) *heavyweight* a) *lightweight*

3.9. **Measured and simulated internal temperatures for two single-zoned buildings in Seville, and Huelva, Spain. Data from field measurements and simulations using the program Quick [31].**

The time lag effect of heavyweight walls is well represented in the *explicit finite difference* or Euler' method (3.10) used in the SERI-RES [51] model to calculate the hourly thermal response of walls. The method operates as a thermal network of nodes the number of which is user-defined for each wall as a function of element thickness.



a) time lag - SERI-RES *b) SERI-RES v. LESO-TMS*

3.10 a) Time delay effect produced by a heavy (0.20 m) and a lightweight structure on the internal temperature. Based on simulations for a single concrete cube using the model SERI-RES. b) Comparison of predictions of mean hourly air and surface temperatures inside a single concrete cube between simulations from SERI-RES and LESO-TMS. A heat pulse of 2 KW is used in both runs.

The prediction of sol-air and internal and external surface temperatures is also possible. The description of the heat storage and all other thermal mass calculations is given in [51] and [52]. The predictions of internal surface and air temperatures of SERI-RES and LESO-TMS are very close to each other. The temperature curve for the internal surface shows a slight difference in the way it reacts to the introduction and the cancellation of heat gains. The SERI-RES curve indicates a gradual and slower drop after the heat gain variation, while the LESO-TMS curve indicates a more abrupt jump.

3.6 Conclusions

The effect of the thermal inertia of buildings under a specific condition of heat gain is determined mainly by the physical properties of the internal surfaces. The thermal response of a room due to the effect of its building mass and the effects of heat gains are well identified by both the diurnal heat capacity and the thermal effusivity.

The calculation of the diurnal response of one side of a building element to an impulse of a heat wave on the other side can be found on the principles of the admittance method. This also gives a procedure to estimate the temperature variation of the wall surface. The diurnal heat capacity method follows this procedure and propose a method for the estimation of internal temperature swings for a whole room or building under the effect of direct solar gains. The main assumption of the model is that the building envelope is well insulated thus, heat flow is single dimensional and no further heat is to be considered in addition to that absorbed by the internal surfaces. An alteration of the equation is proposed here to apply the method for conditions of overheating using a total heat gain value that accounts for internal gains.

The thermal effusivity proposes the use of a step function response of a building zone to account for an intermittent heat gain instead of a harmonic excitation. A mean value of thermal effusivity for a room can be used for an area weighted average akin to the *DHC*. Comparisons between the internal temperature predictions using the *dhc* method, the SERI-RES program and temperature data from field measurements are presented in chapter 7.

3.7 Nomenclature

Y	= admittance	W(m^2 K)
Yt	= total admittance	W/K
A	= area of element	m^2
λ	= conductivity	W/m K
ρ	= density	kg/m^3
c	= specific heat	KJ/kg K
P	= diurnal cycle	24 hours
Φ	= total heat flow	W
t	= time	h
A	= area	m^2
U	= U value or air-to-air transmittance	W/m^2 K
Tsol	= sol-air-temperature	°C
Ti	= indoor temperature	°C
ΔTi	= swing of indoor temperature	K
dcr	= decrement factor	
tlg	= time lag	h
$\Delta\Phi$	= swing of heat flow	W
Te	= environmental temperature	°C
Tr	= mean radiant temperature	°C
Ta	= indoor air temperature	°C
Ts	= internal surface temperature	°C
To	= outdoor air temperature	°C
ΔT	= outdoor-indoor temperature difference	K
qv	= ventilation heat loss (0.33 * N * V) or (1200 * vr)	W/K
qc	= heat loss by conduction (sum U*A)	W/K
N	= air changes per hour	N
V	= room volume	m^3
vr	= ventilation rate	m^3/sec
fo	= surface conductance	W/m^2 K
Rso	= surface resistance	m^2 K/W
asg	= alternating solar gain factor	
hlc	= heat loss coefficient	W/K
ω	= angular frequency	2π/P
x	= element thickness	m
δ	= harmonic penetration depth	m
ξ	= ratio of layer thickness and penetration depth	x/δ
d	= thermal diffusivity	m^2/sec
b	= thermal effusivity	b
C	= thermal capacity	J/K
$\varkappa$	= areal thermal capacity	
dhc	= diurnal heat capacity of element	W/m^2 K
DHC	= diurnal heat capacity of room or building	W/K
τ	= time constant	h

Part II

Field Experiments

4

Case Study 1: Managua

4.1 General Strategy for Field Experiments

The strategy adopted for the field work experiments in this investigation was divided into two stages. The first stage presented in this chapter, provided an overview of the effect of the thermal inertia and night ventilation in buildings in warm conditions. This included the recording of spot temperature measurements at different times of the day on two typical administrative buildings in the city of Managua, Nicaragua in Central America. The analysis of the results obtained was followed by a plan of thermal simulations aimed at identifying the influence of thermal mass and night ventilation on a multiple zoned model using weather data for Managua into the thermal analysis program SPIEL [29]. The second phase of the field work experiments were carried out with the thermal monitoring of four buildings located in the southern region of Andalucia in Spain for a longer period of time and with an extended monitoring programme, see chapter 5. The subsequent data analysis was followed by the parametric studies performed with the use of the programs SERI-RES and BREEZE, see chapter 6.

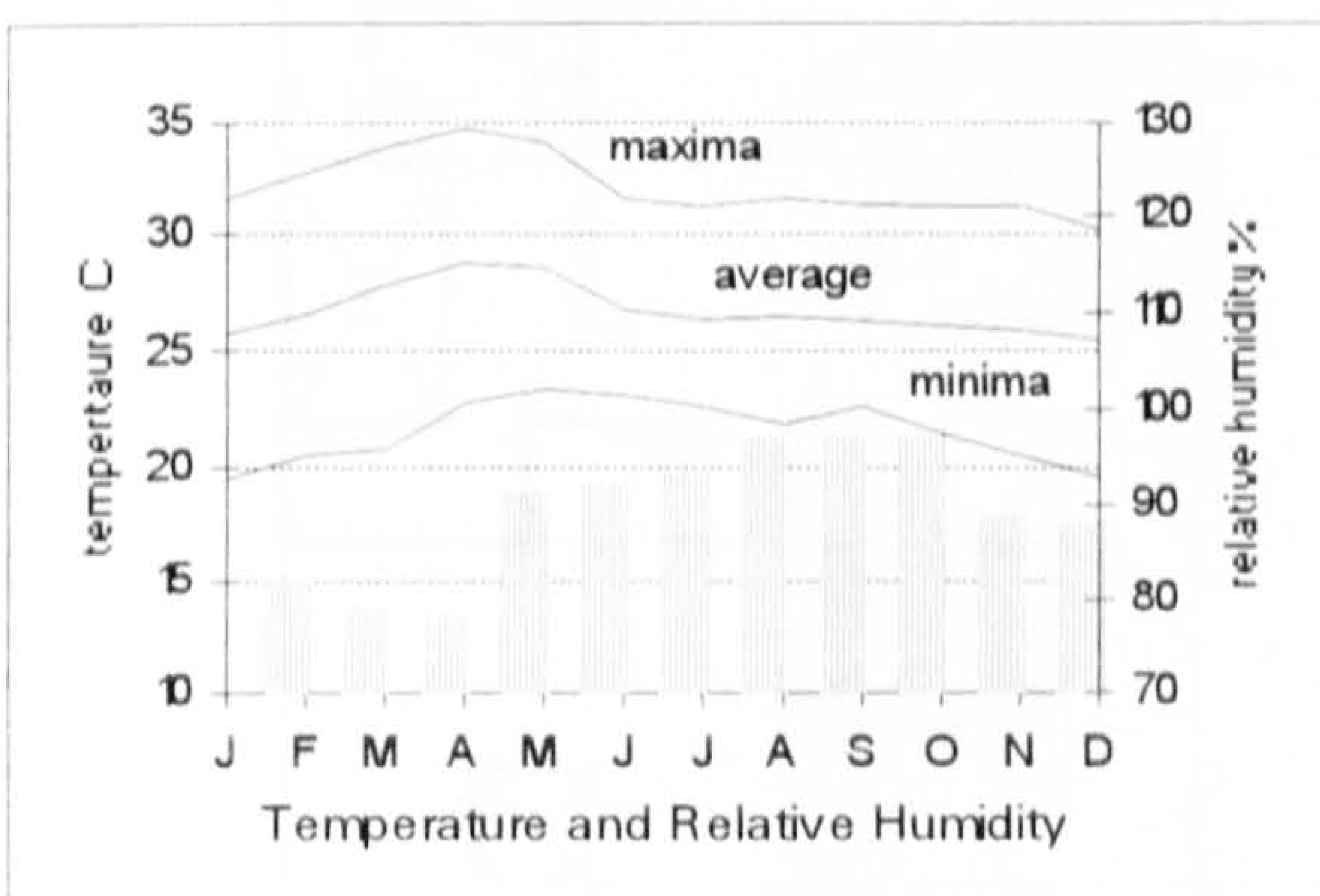
4.2 Lightweight Versus Heavyweight

This chapter describes the field experiments carried out on two case study buildings located in Managua and a series of parametric studies. The study focuses on the comparison between lightweight and heavyweight construction types and aims at observing the effect of the thermal capacity on the building's internal climate under various ventilation conditions, day-time, continuous and night-time. The results of both the measurements and the thermal simulations, helped to derive preliminary conclusions.

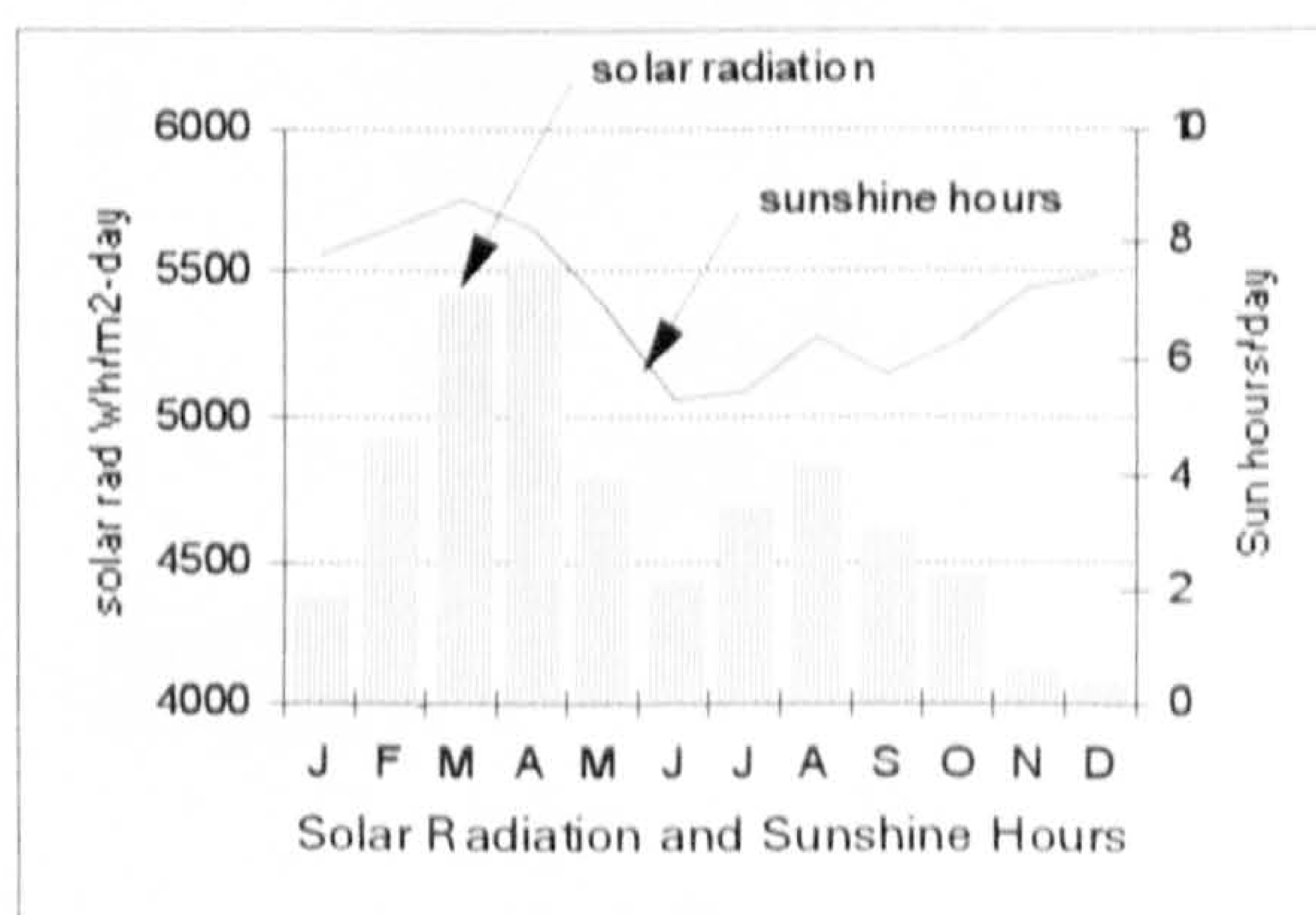
Heavyweight construction is a distinctive feature of traditional architecture in Central America. Administrative and residential buildings of the colonial period are characterised by their massive structure, thick walls and heavy roofs. Today, lightweight-uninsulated buildings are preferred and have become the most common form of contemporary construction. Although in the warm and humid conditions of this location, indoor temperatures during the day often rise above comfort, these lightweight structures are able to accelerate the process of heat dissipation through the structure at night as the external temperature begins to drop. This effect is particularly beneficial in residential buildings where night time comfort is essential. However, when lightweight components are used for office spaces, indoor conditions at working hours often result in overheating and frequently these spaces have to rely on continuos air conditioning. The small inertia effect of the envelope, offers little resistance to the effect of solar radiation, both through the roof and walls consequently, heat gains are experienced from the early hours of the day, progressively elevating the internal temperatures as the outdoor environment becomes warmer. Because the internal gains of these spaces are also high, the heavy mechanical cooling provided as a result, makes such buildings impractical and expensive to maintain. This section summarises the results of a series of analytical studies carried out to observe the effect of thermal mass and its potential benefit for office buildings in Managua.

4.3 Climatic Data

Nicaragua is located between the 11º and 15º latitudes of the northern hemisphere. Managua, the capital city, lies on the shore of the lake Managua on the west part of the country. The climate of this area is dominated by the two main annual periods: the dry (October to April) and the rainy season (May to September).



a) temperature and relative humidity



b) solar radiation and sunshine hours

4. 1 Climate Data for Managua

Climate conditions within the country vary according to altitude and coastal proximity but it can be asserted that the average temperature throughout the year rarely ranges between a mean minimum of 25 ºC in the humid season and a mean maximum of 29 ºC in the dry season. The average relative humidity is fairly high for a great part of the year reaching 80% in the humid period and not falling below 60% during the dry season.

4.4 Field Temperature Measurements

Spot temperature measurements were taken on different days inside two selected buildings, with different construction specifications and representative of the typical office building in Managua, 4.2. The highlighted zones on the plans show the rooms where measurements were taken. The description of the rooms is given in table 4.1.

4.4.1 Case 1 Contemporary Building

This single story office building was constructed in the late 1970's originally as a residence and like most of the current small scaled office buildings in Managua, it was later refurbished to house an administrative office building. The site is located on a low rise - low density urban area in the outskirts of the city, and the plan has a north-east south-west orientation.

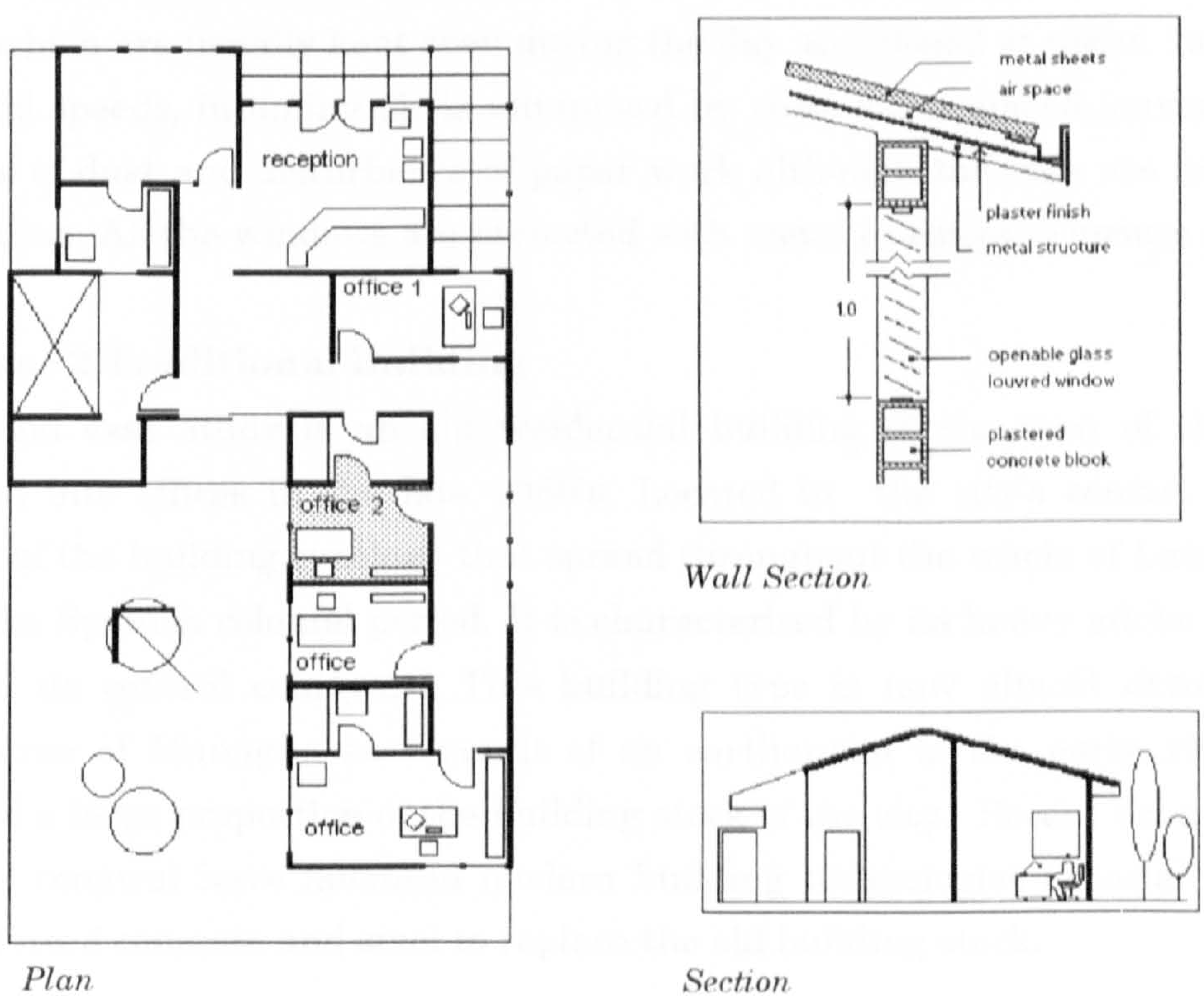


Fig 4.2 Case 1: Contemporary Building

4.4.1.1 Envelope and Internal Mass

The building characteristics of this example are typical of contemporary construction in Managua. The structure of the walls is made up of hollow blocks with plaster finish and painted white. There is no constructional distinction between envelope walls and internal partitions. The roof is also a lightweight combination of metal and wooden rafters as a structure for the metal-sheet roof covering. With the high humidities experienced in long periods of the year, the surface of the metal sheets are usually dark and rusty and although some have been replaced, the greater part of the surface of the roof remains unchanged elevating the absorbance of the roof. The concrete slabbed floors are covered with light coloured granite tiles.

4.4.1.2 Ventilation and Shading

The building is free running and the only mechanical assistance to control the internal climate come from the ceiling fans on some of the office rooms. Most of the offices are located on the narrow south-west wing where the afternoon sun creates most of the overheating problems. The corridor on the east side is well protected against direct solar radiation by the overhang that shades the high positioned windows of the east wall. The offices are well lit and the windows are made of glazed louvers which are usually kept open during the day and closed at night. In periods of high wind speeds, incoming air is minimised by closing the glazed louvers to avoid problems of dust and disturbance of paper work although the fans are in operation most of time. All the windows are protected with metal gratings to ensure security.

4.4.2 Case 2 Traditional Building

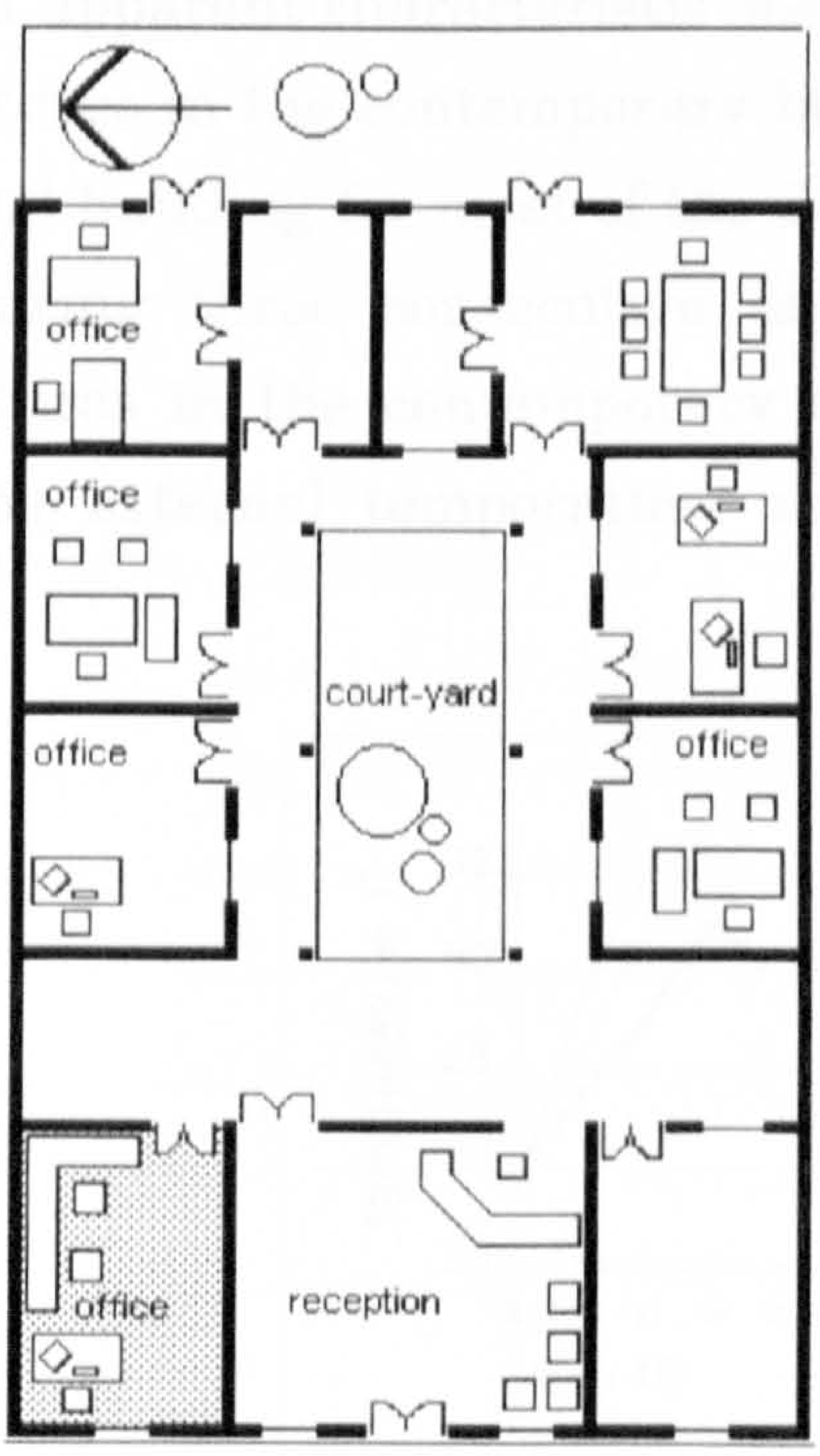
The second case study is an old residential building of the turn of the century converted into offices in the late 1980's. Located in the city's centre, this is an example of the building typology that spread throughout the whole of Latin America during the Spanish colonial period. It is characterised by its heavy adobe walls, roof tiles and its central courtyard. This building type is now almost extinct on the central area of Managua as a result of an earthquake in the early 1970s which destroyed a large proportion of the building stock of the city. Recent urban plans for the city's renewal have favoured modern building technologies especially with the use reinforced concrete and steel to replace the old building stock.

4.4.2.1 Envelope and Internal Mass

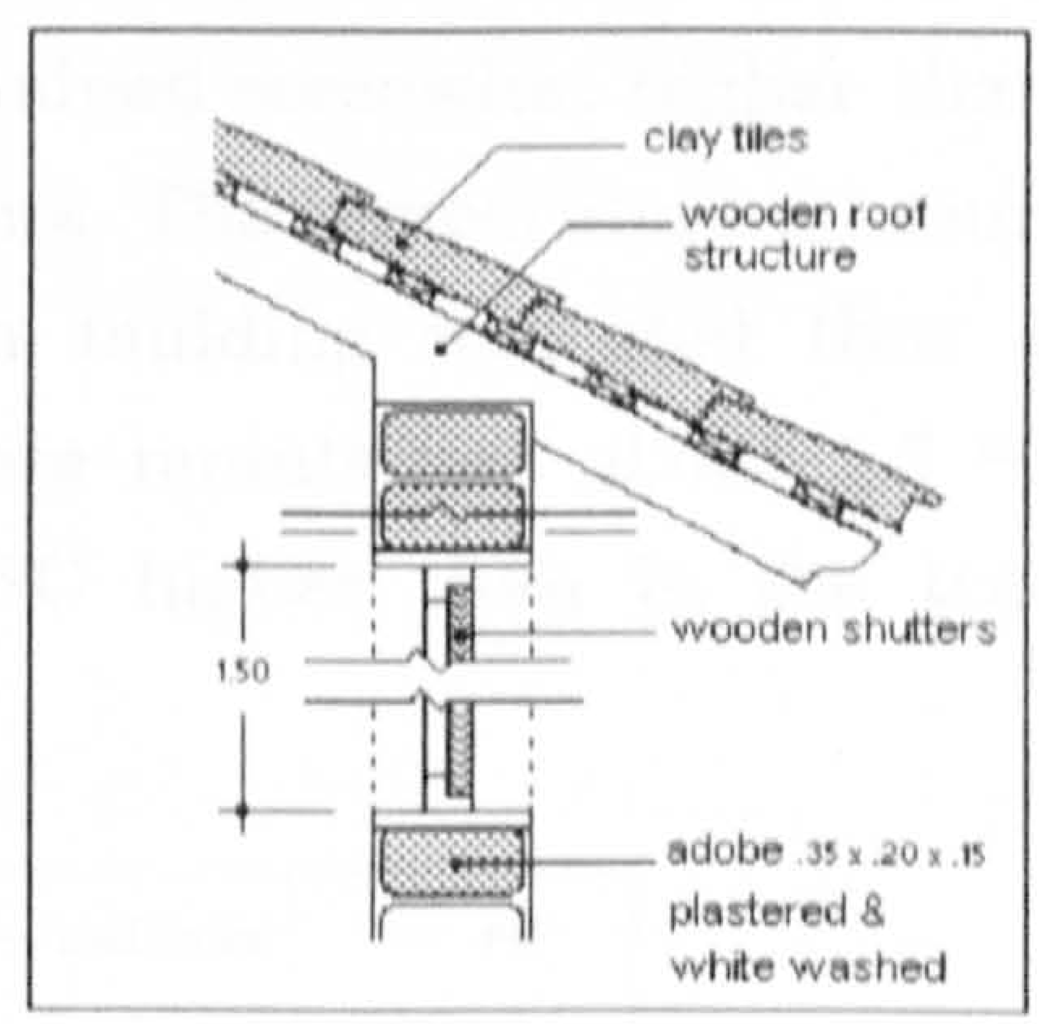
External walls are made of heavy adobe blocks strengthened with other mixed materials and rubble. Most of internal partitions are constructed in the same fashion except for some additional elements introduced recently which used hollow block masonry. A major feature that distinguish these buildings from the contemporary ones is their large ceiling height on the main rooms and corridors. The building has an average ceiling height of 4 to 4.20 m and because the average area of rooms is also larger than the area of rooms in modern buildings this leads to assume that in general, there are greater areas of wall and ceilings surfaces exposed internally in traditional buildings.

4.4.2.2 Ventilation and Shading

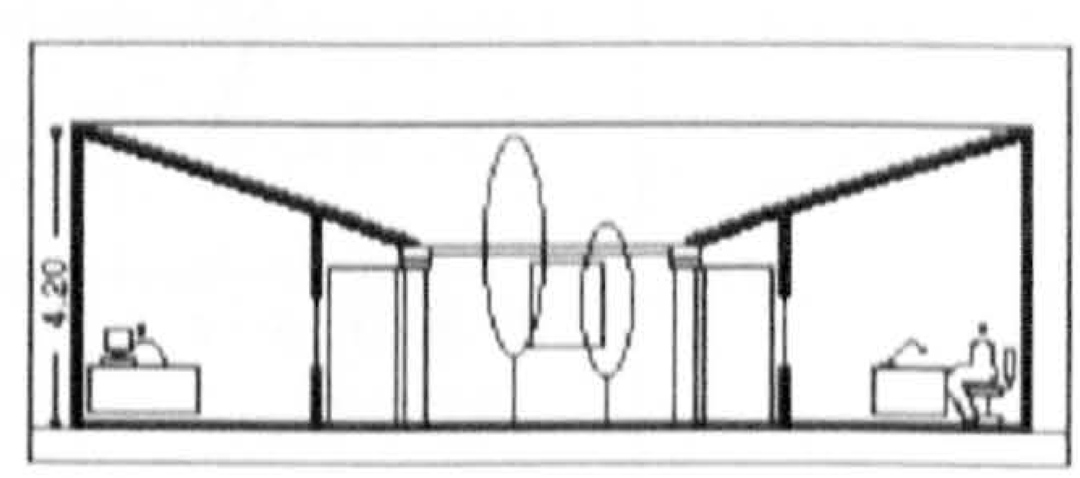
The window type and size has also changed throughout the years. The traditional building, has a very low window to floor ratio compared to the modern building and instead of glazed louvers the windows are protected by wooden shutters. All the windows on the office rooms facing the central court-yard are well shaded at all times of the year by the corridor-veranda although despite their location toward the central patio, all the rooms have front windows providing only single-sided ventilation.



Plan



Wall Section



Section

Fig 4.3 Case 1: Traditional Building

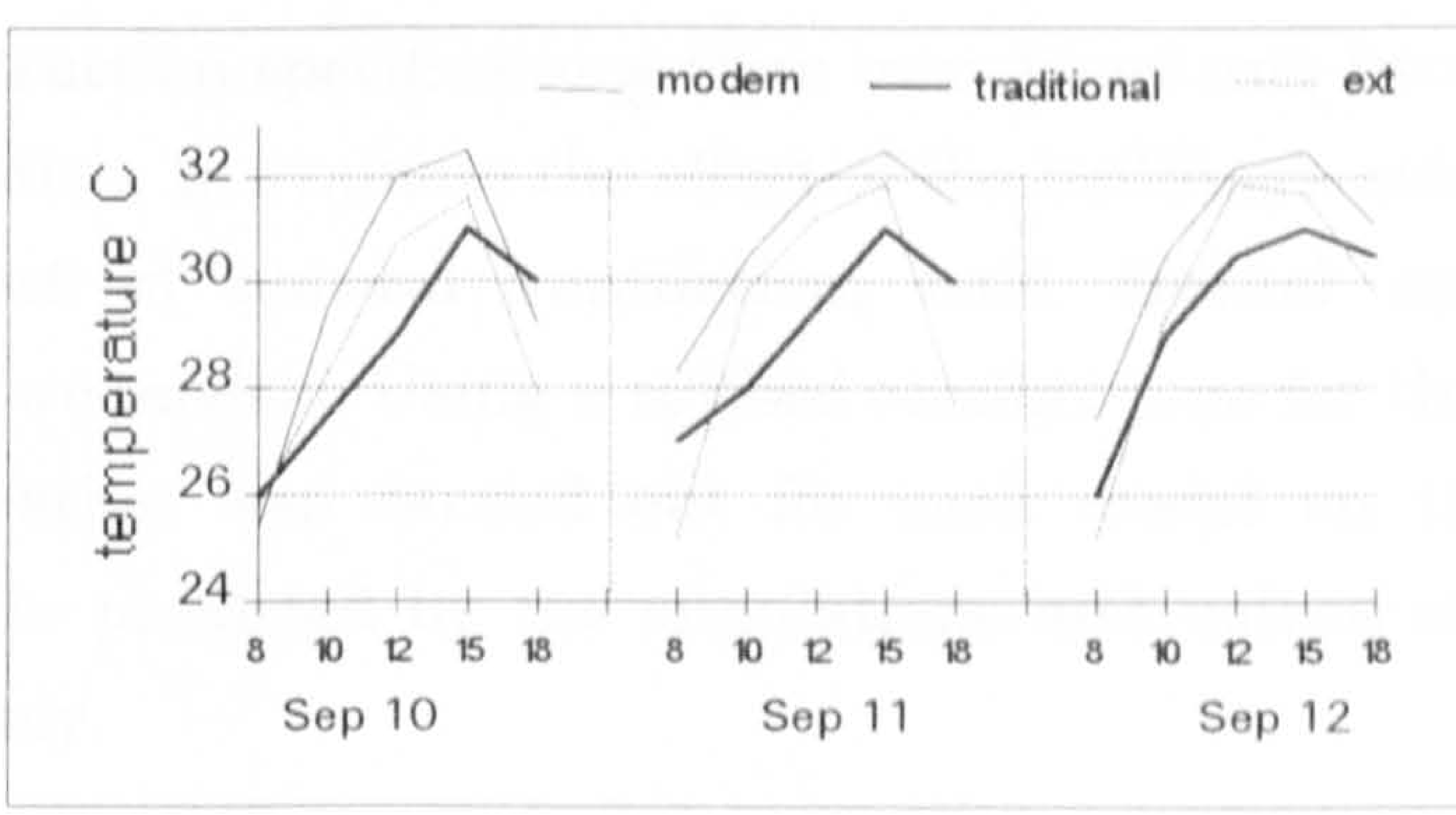
The large front doors to the reception are usually open to increase air movement inside the rooms creating a cross ventilation pattern with the internal patio although this is used only during day time hours. Because the high position of the sun, the floors of the corridors around the patio receive direct radiation at some times of the day despite the large overhangs, but their clay tiled and dark coloured surface help reducing the reflections toward the rooms. The building is not air conditioned but ceiling and portable fans are used inside the offices.

Table 4.1 Case Studies Room Data

room data	*contemporary*	*traditional*
area (m^2)	13	31.5
volume (m^3)	31	126
window /floor (%)	16	7.14
occupants	2	3
orientation	NE	W

4.5 Results of Measurements

The most apparent characteristic observed on these experiments is that the internal temperatures in the contemporary building remained somewhat higher than in the traditional building for most of the day-time hours. The temperature measurements taken during three consecutive days on each building indicated that daytime temperatures in the contemporary building were maintained about 1.5 °C -2 °C above the external temperature and 2 °C-3 °C higher than in the traditional example.



4.4 Spot temperature measurements for three days in the traditional and modern buildings.

The lighter structure of the modern building, as it was expected, responded quicker to the effect of the external temperature variations showing a closer relation to the outdoor temperature curve. The temperature swing was also an important indicator of the effect of the thermal mass on the thermal conditions of the buildings. Despite the limited frequency of the spot temperature readings, there were clear suggestions that the internal air temperature on the modern building had a greater diurnal swing (between 8 K and 10 K) than the traditional (around 5 K). However, no significant difference was observed with respect to the time lag. As a result, the internal temperatures on the traditional building were maintained below the external temperature for most of the day, although it can be anticipated from the graphs that at night the temperatures will not drop as low as they did in the lightweight building.

The point where the internal temperature of the becomes higher than the external occurs at about 5:00 p.m. which is around the time when the occupants leave the building. One possible explanation for the more favourable thermal response of the traditional building is the larger ceiling height. A higher ceiling height indicate first, that there is a lager exposure area of the surfaces on the walls and that the spaces have a higher volume enhancing the effect of stratification. The larger surface exposure of surfaces increase the heat exchanges with the internal air. The larger room volumes may have an influence on the time that temperatures take to build up in the interior.

4.6 Parametric Studies

Using the dynamic thermal simulation programme SPIEL [29] lightweight and heavyweight construction specifications were introduced into two building models of identical configuration, to evaluate the effect of the building's mass on their internal climate. The effect of natural ventilation, both diurnal and nocturnal, was considered in the two models. Using a revised comfort zone for this climatic location, the comfort evaluation was carried out for each model on the basis of hourly temperature results predicted by the simulations and values of relative humidity calculated separately.

4.6.1 Model description

The model was introduced into the program as a series of thermal zones which react according to the thermal interactions between its components, internal gains and the external environment and which are sensitive to variations in area, volume, orientation, construction specifications and weather data. In order to illustrate graphically the numerical thermal model introduced into SPIEl, a schematic version of a hypothetical office building is given in 4.5. The two main variants used on this model are the open and the cellular plans. The open plan model represents a section of an office building without internal partitions. The model is made up of two zones - the corridor and the office space -. These are oriented north-south to minimise the effect of solar gains incident on vertical surfaces which affect mostly the west and east facades according the local solar altitude. The cell plan model was derived from the open plan model with the variant that the office area was subdivided into six cellular offices all connected to the corridor. In order to preserve the comparability with the open plan, aspects of orientation, dimensions of total floor and window area, volume and occupancy patterns remain unaltered. The central parameters for comparison were the thermal mass and ventilation. Each model's performance was analysed under separate conditions both of structural weight and of air changes per hour.

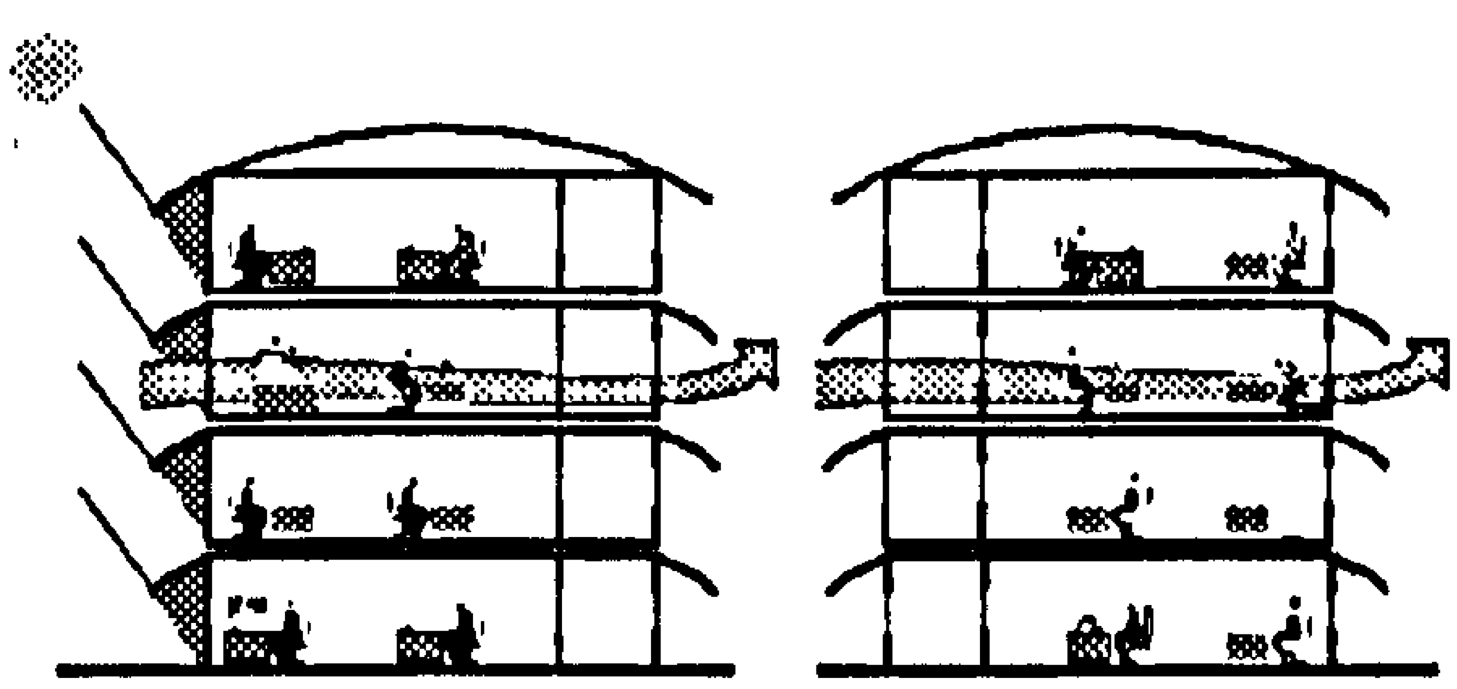
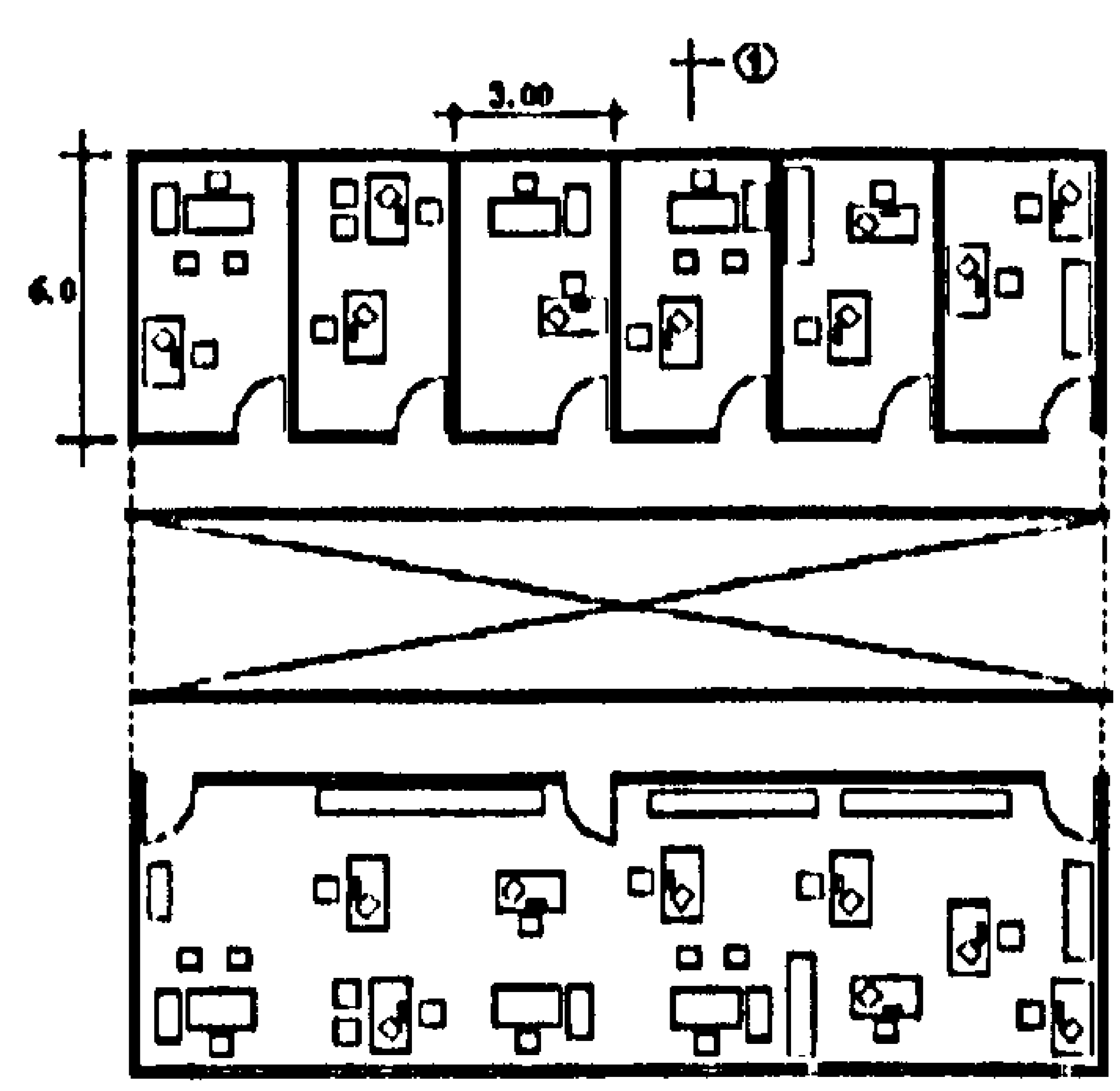
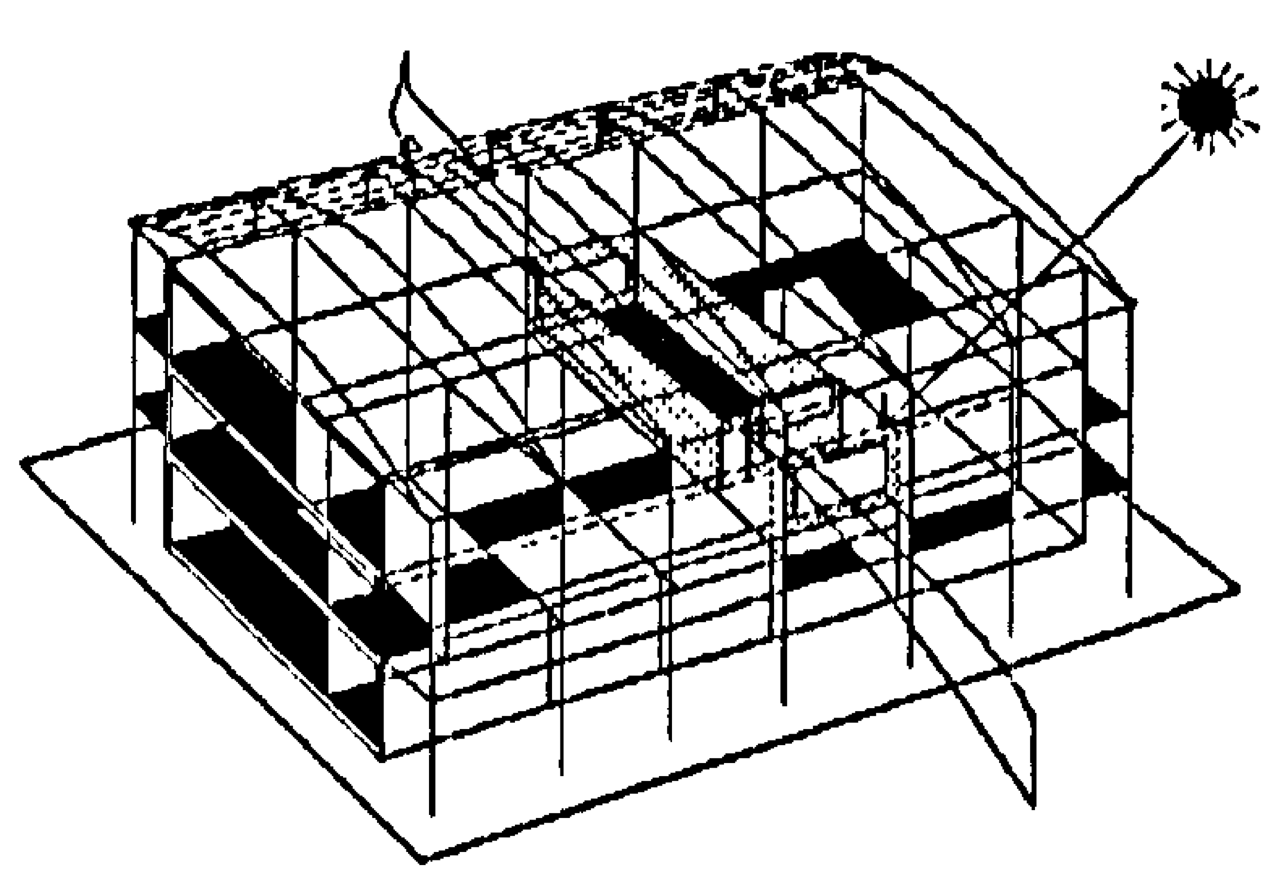


Fig. 7 SECTION

Section



plan



Axonometric

4.5 Reference zone modelled for simulations

As to constructional specification, two general categories were used: lightweight and heavyweight. Both categories were established calculating the thermal properties of typical building elements currently used in Nicaragua (lightweight construction) and calculating thermal properties of heavier structures which are less common practices but using materials locally available (heavyweight construction).

Ventilation calculations were carried out according to local air speed values, volume and window areas. All other data were kept the same for both models so that the significance of thermal mass and ventilation could be observed. The unit space has a floor area of 108m^2 and a volume of 259 m^2 with an occupancy density of 4.5m^2/person. The total capacitance of the building envelope and the ventilation rates were the two major variants considered for the parametric studies.

Table 4.2 Properties of Building Fabric

model	*U value (W/m^2K)*			*Total Capacitance*
	wall	*roof*	*floor*	*(Wh/m^2K)*
lightweight	2.0	1.5	1.8	44
heavyweight	1.8	1.3	1.5	495

The orientation was maintained unchanged (north-south) for both cases and the simulations were carried out for April, the period of the year with the highest temperatures. Tables 4.2 and 4.4 summarise the building data introduced into the program. It is worth mentioning that the overall storage capacity of the heavyweight building was not only increased by using thicker walls and roofs but also by the introduction of internal partitions into the unit.

Table 4.3 Ventilation Rates

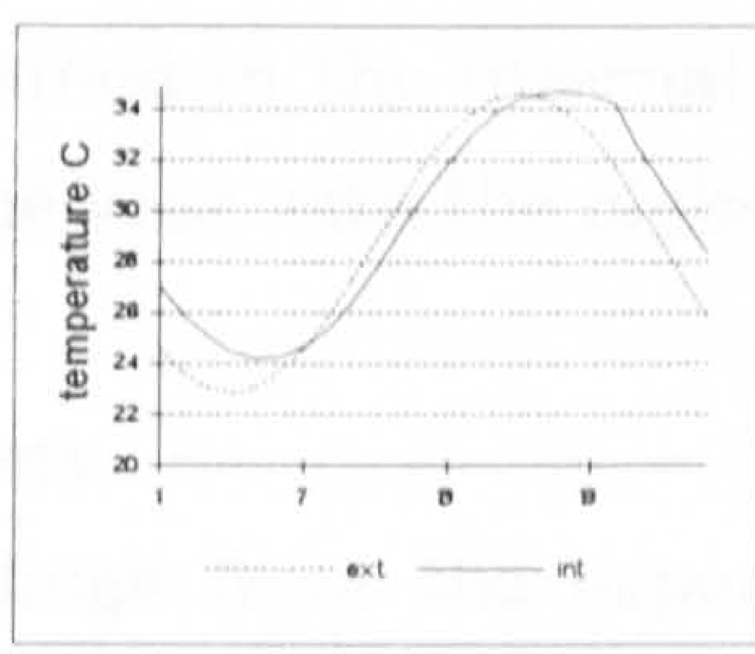
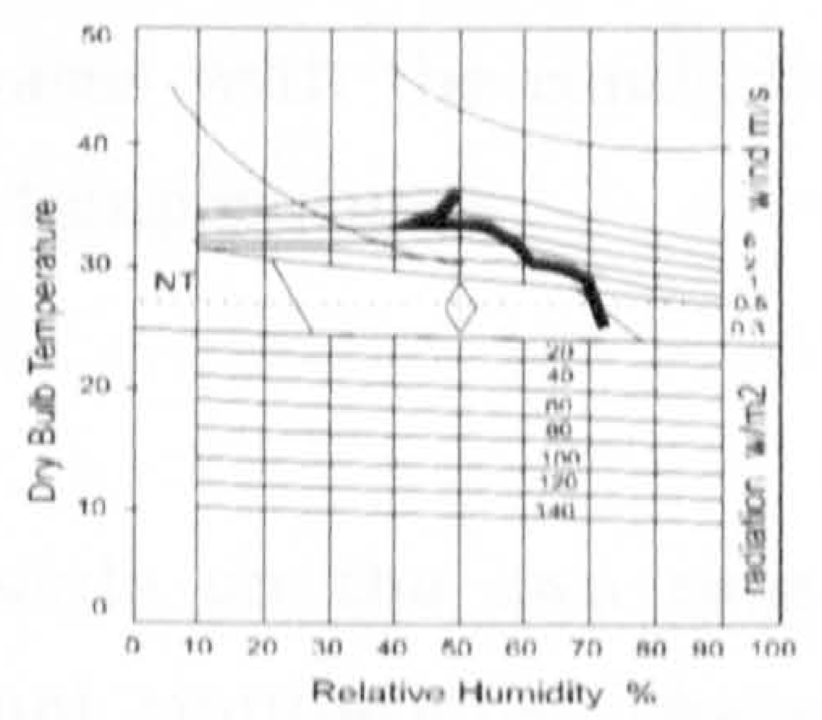
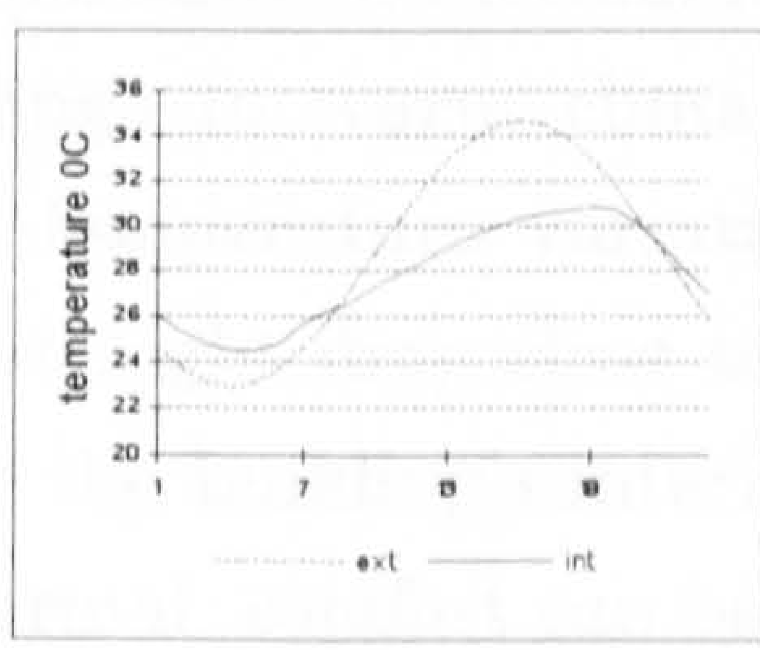
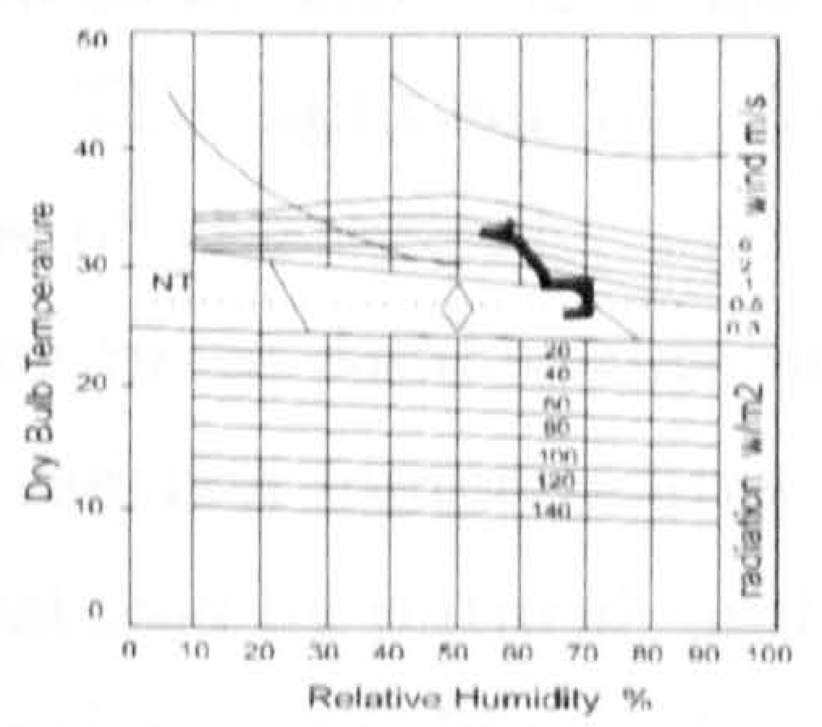
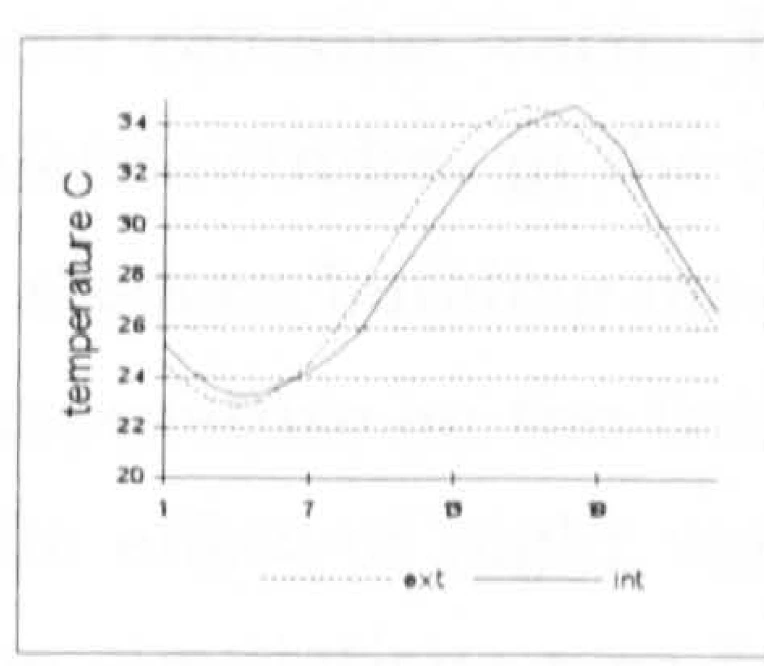
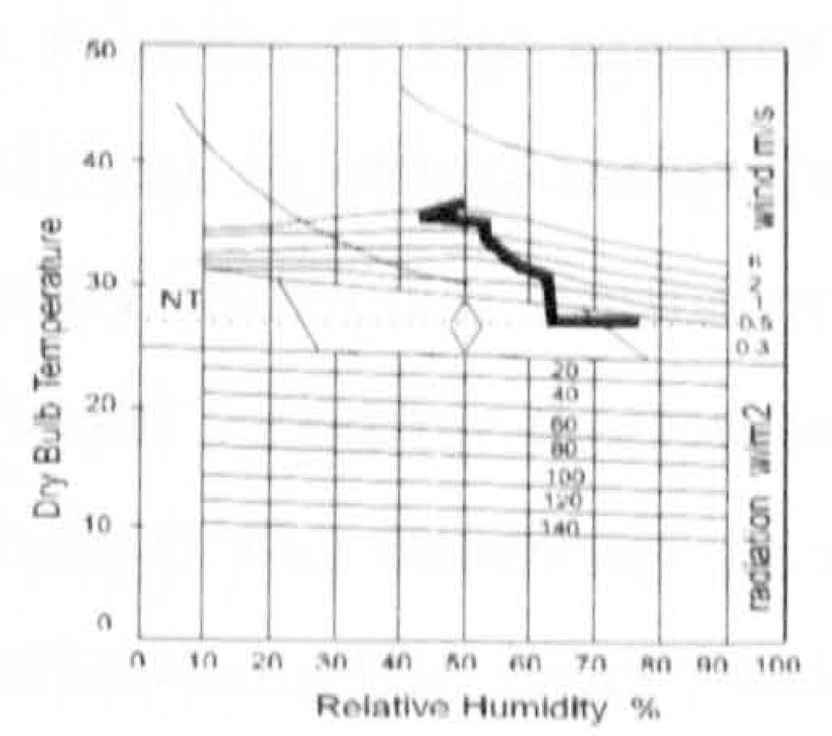
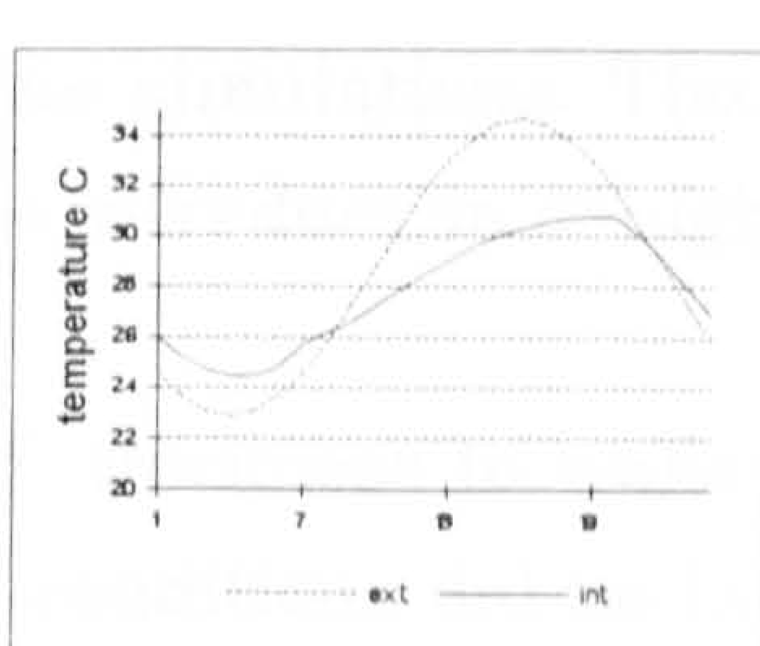
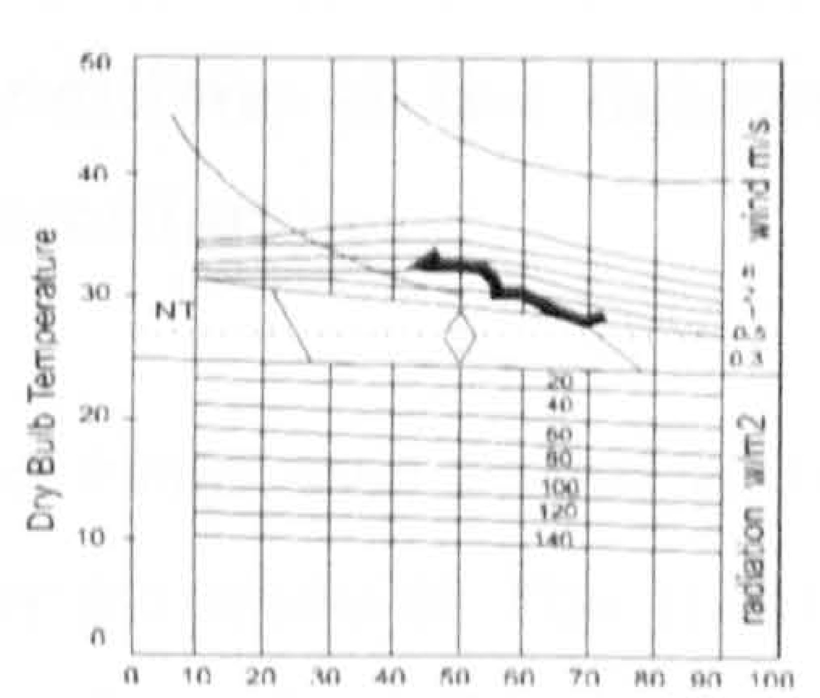
period	*ventilation rate*
	m^3/sec
day-time	0.36
night-time	7.2

Day-time ventilation rates resulted from the balance between the requirements for fresh air, the control of relative humidity and the reduction of ventilation gains in order to maintain the minimum temperature possible inside the enclosure. For night-time ventilation, maximum values were estimated according to local wind speed and prevailing wind direction. Maximum window aperture was given to all offices for night-time cooling assuming measures of security can be taken.

4.7 Thermal Comfort Assessment

The comfort assessment of the models was carried out using a defined comfort zone for Managua following the concept of neutral temperature, [55] and a revised bio-climatic chart [67], [68]. The comments on comfort refer to day-time occupancy.

Table 4.4 Summary of Results

Variable	Temperature	Comfort Analysis	Observations
			Thermal comfort can only be achieved during the morning hours. The spaces quickly begin to warm up becoming too hot by the early afternoon. Comfort by air movement is possible but at air speeds too high for office work.
			With a constant air movement of at least 1.5 m/s, it is possible to maintain the internal spaces within the limits of comfort. This air speed may disrupt office work.
			With an increased night ventilation rate the thermal comfort obtained during the morning hours cannot be maintained for the rest of the day. The lightweight envelope does not prevent heat from flowing inwards.
			Thermal comfort can be achieved in a heavyweight night ventilated structure throughout the working hours provided there is a constant air movement of at least 1m/s.

Aided by the psychrometric chart, the internal relative humidity was estimated considering the additional moisture produced by the occupants, the air change rate and the external relative humidity, (see Appendix 6 for calculations). The metabolic rates and Clo. values for the occupants were defined according to the category of sedentary work (1.2) and typical summer clothes (0.5) respectively. The resultant indoor temperatures generated by the thermal simulations and the corresponding relative humidity values for each variant, were plotted on the chart for each of the working hours. The plotted values show the relation between the environmental conditions obtained in the internal spaces with the comfort zone defined for April, the period of the year with the highest temperatures.

4.8 Conclusions

The main findings from the experiments on the two case study buildings were confirmed by the results of the thermal simulations. The results of these studies support the importance of thermal mass as an environmental moderator for daytime occupied buildings in warm climates. The lightweight building responds more quickly to the temperature variations of the outside, and consequently, internal temperatures at night drop close to the more comfortable outdoor levels, although during the day the building's interior reaches temperatures which are beyond the limit where thermal comfort can be restored by natural ventilation. The increase of thermal capacity in the building envelope stabilises the internal temperatures keeping conditions cooler than the outside during the day-time hours although at night the interior remains warm. The results of the measurements also correlated with the parametric studies in the resultant internal temperature swings of the two buildings. The modern building measured showed a temperature swing of about 10 K while the temperature on the traditional building fluctuates around 5 K from the mean. As to the effect of night ventilation the increase of night air change rates according to the simulations was beneficial on the heavyweight model. Its heavier structure was able to maintain during the day the influence of night time cooling. A temperature difference of 5 K- 6 K at peak hours with respect to the outside was suggested by the simulations. The conditions of the lightweight version were not improved by the introduction of night ventilation.

The addition of thickness to walls and roofs was found to have a limit point from where thermal conditions did no longer improve in the interior. The importance of internal layout was highlighted by the fact that the lowest internal temperatures were obtained when the overall thermal capacity of the building was increased not only by the increment of thickness of the building elements but also by the introduction of internal partitions for each individual office (from open to cellular plan) which provided greater exposed surface area of the thermal mass to exchange heat with the room air. This association was also made with the results of the field measurements. The selected building with massive construction (a traditional adobe wall and clay tile roofed building) had larger wall surface areas as ceilings heights in those buildings are generally greater than in contemporary constructions.

Although the results of the study may encourage further investigation on the effectiveness of thermal mass for indoor cooling in warm and humid climates, it is important to bear in mind some aspects which may affect its application for that specific location. The temperature swing in Managua is not large enough (around 10 K during the warmer period) to ensure rapid dissipation of heat by natural convection. It has been suggested that for night cooling strategies to be effective, the night-time temperature will have to be lower than the comfort limit [8]. If efficient cooling by convection is to be promoted, the conductance of the internal surfaces will have to be further increased, especially at those hours when temperatures drop to the minimum (mid-night and early morning) and because nocturnal wind is not always reliable or continuous, some air may have to be supplied with fans although in practice these are never left in operation over night.

The decision as to whether project a massive building with lower day-time ventilation rates and high night ventilation instead of a lightweight building with high continuous ventilation as it is often recommended for these climates, will have to be carefully considered early during the design process and will depend on the particular conditions of the site, building type etc. In practice, it is frequently observed that lightweight buildings which are designed to be naturally ventilated and measures to minimise heat gains, such as the provision of shading, ventilated roofs, planting and light coloured surfaces have been taken, are often maintained closed due to problems of noise, dust, privacy and usually the use of fans provides a replacement for the required air movement inside the spaces. The balance of the results obtained, both from the field measurements and from the thermal simulations suggest that the presence of massive elements in the structure may represent significant advantages for reducing the thermal discomfort produced by overheating in administrative buildings in Managua.

5

Case Study 2: Andalucia

5.1 Methodology and Strategy

From the conclusions described in chapter 5, it was felt that a more detailed analysis of the thermal mass effect in buildings was required, for which a second set of field measurements was planned. The location chosen for this experiments is the region of Andalucia in the south of Spain. The larger daily temperature amplitude of that region, which provided a more appropriate climate conditions for the study of thermal mass and night ventilation in buildings and the strong local tradition for massive construction were among the main reasons for this selection. This section reports on the data collected during 4 weeks of field measurements carried out in 4 buildings situated in the areas of Seville, Carmona and Huelva. Two recent and two traditional buildings of different construction types, were selected as case studies for the experiments which aimed at identifying thermal characteristics related with the effect of the building mass and providing data for comparison with the subsequent thermal mass analysis carried out in the parametric studies in chapter 6.

5.1.1 Thermal Measurements

Using flying-lead tinytalk data loggers, a number of temperature measurements were simultaneously recorded for an average 1 week per building. The collected information for each building is the following:

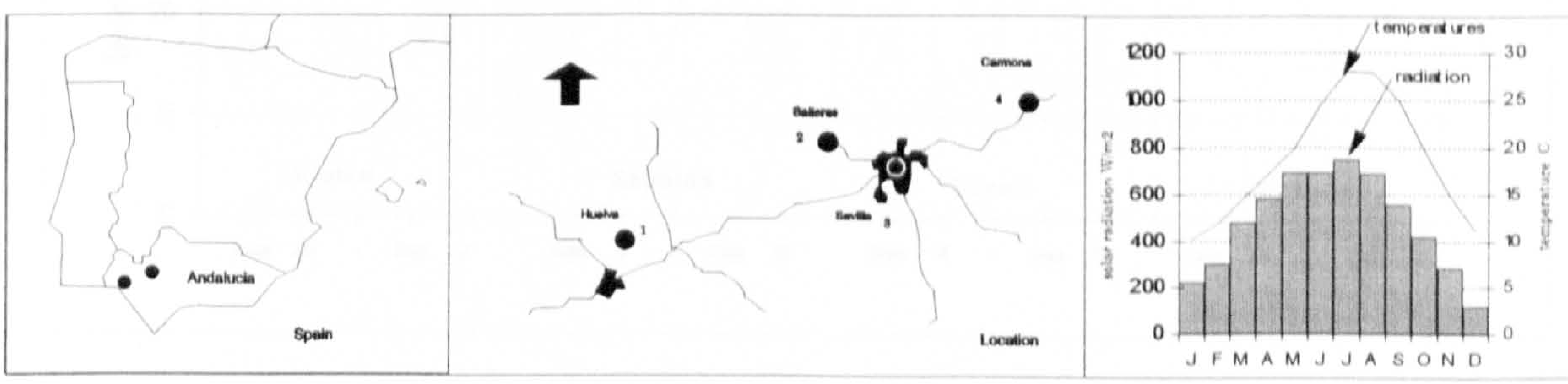
1. external air temperature
2. external wall surface temperature
3. internal wall surface temperature
4. internal air temperature
5. partition surface temperature
6. ceiling surface temperature

The temperature measurements of external wall surfaces were aimed at observing the effect of direct solar exposure of different types of opaque elements on the internal surface temperature. This provided relevant information for time lags and heat gains through fabric. The internal surface measurements in turn, helped to observe their influence on temperature of the internal air and gave an indication of temperature distribution within the rooms. The recordings of internal partitions provided data for the analysis on mass location. Surface temperatures both internal and external were taken using an insulation material to protect the sensor from the influence of the surface resistance and from radiation from solar and/or surrounding surfaces.

Spot measurements of temperature, globe thermometer and air velocity were also taken. The location of the sensors throughout the buildings are shown on the plan of the buildings according to the numbers on the list above.

5.1.2 Location and Climate

The micro climate of the specific the location of each building vary according to elevation, coastal proximity and urban density, however the main climatic configuration in terms of temperatures, solar radiation, and wind characteristics are very similar and locally can be used equivalently for design purposes.

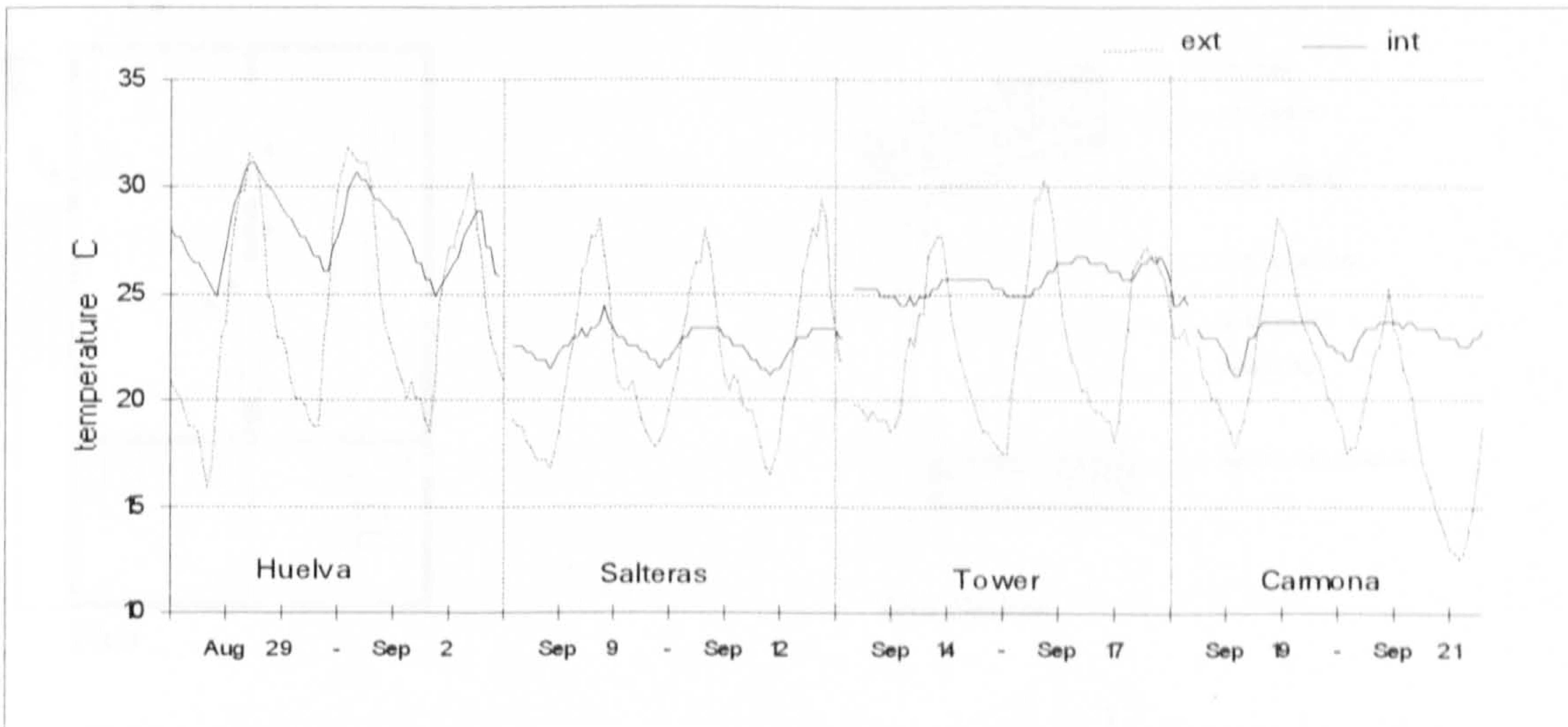


5.1 Location of case study buildings and weather data for Seville

5.1.3 Selection Criteria

The constructional features of the buildings was one of the criteria used for the building selection. The features of the selected buildings vary with local characteristics and period of construction. This distinction allowed the comparison of the thermal reaction between heavy and less heavy structures for the envelope and internal mass elements. Modern buildings in the region tend to be constructed with lighter materials and larger glazed areas than the old traditional Andalucian buildings. Another criterion for the selection of the buildings was to chose spaces with different internal geometry. This was with the purpose of having the four spaces with different mass to floor ratio values so that this aspect would be accounted for in the analysis. The heat gain characteristics of the selected buildings was given special consideration. It was made sure direct solar radiation was minimised and although the internal gain schedule varied in each case, it was possible to record a number of days without the effect of internal gains in all the buildings.

As an initial comparison of the thermal performance of the four buildings, graph 5.2 shows the internal and external temperature recorded during three consecutive days in each of the buildings. This gives an idea of the typical response of the buildings and shows simultaneously the outdoor temperature profile recorded in the four locations. The rest of the data is presented separately for each building together with the corresponding observations.



5.2 External and internal temperatures for three consecutive days in the four buildings.

5.2 Building 1: *Huelva*

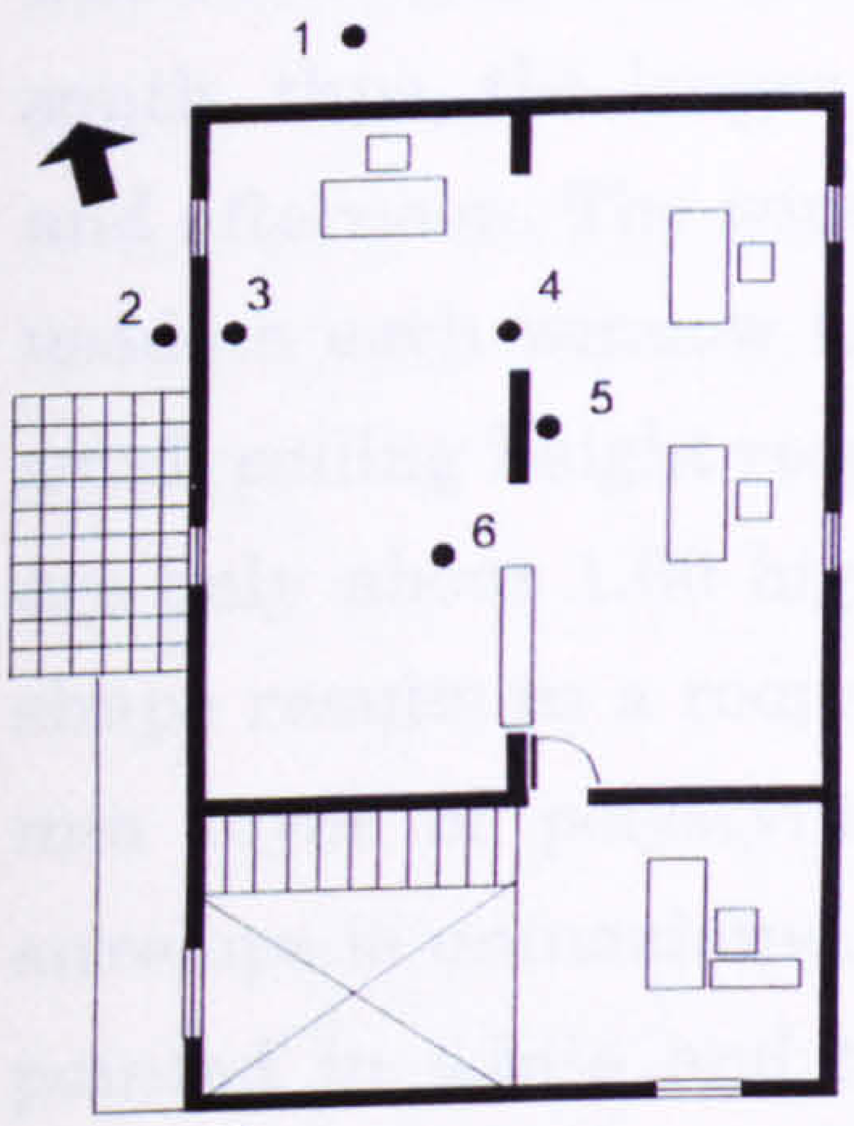
The city of Huelva lies on the south-west coast of the region of Andalucia at approximately 100 km from Seville and it is the capital city of the province of the same name. The first selected example for the experiments is located in this zone and was monitored for a period of seven days from the 27th of August to the 2nd of September 1993.

5.2.1 Site Location and Climate

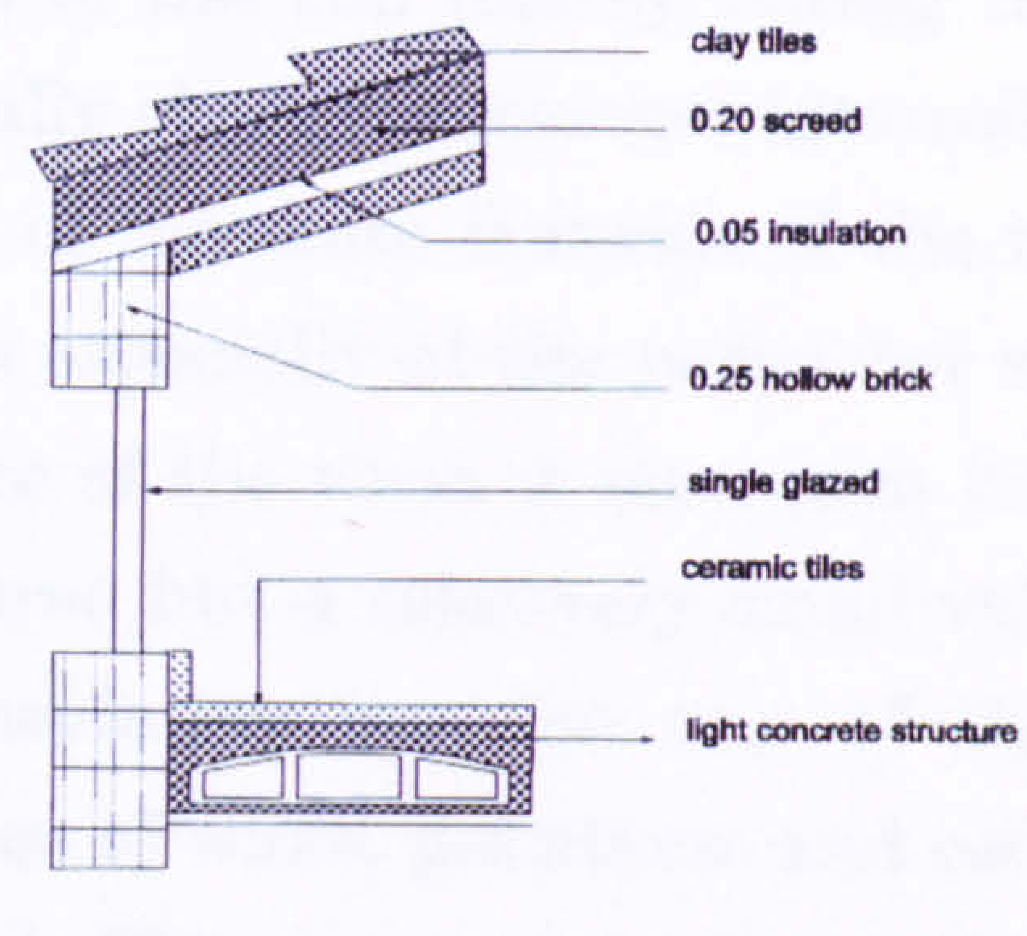
The site is located around 15 km to the north of the city of Huelva, with an elevation of 26 m above sea level in an area devoted mainly for agricultural development. The surroundings of the building are dominated by the open field, although a few low rise detached buildings nearby, complete the built environment of the area. The climate of this region is classified maritime with temperatures ranging between 6.7 °C - 16.5 °C in winter and between 19 °C - 31.8 °C in the summer. Winds are predominantly south-west and the relative humidity ranges between 50% to 80%.

5.2.2 Building Description:

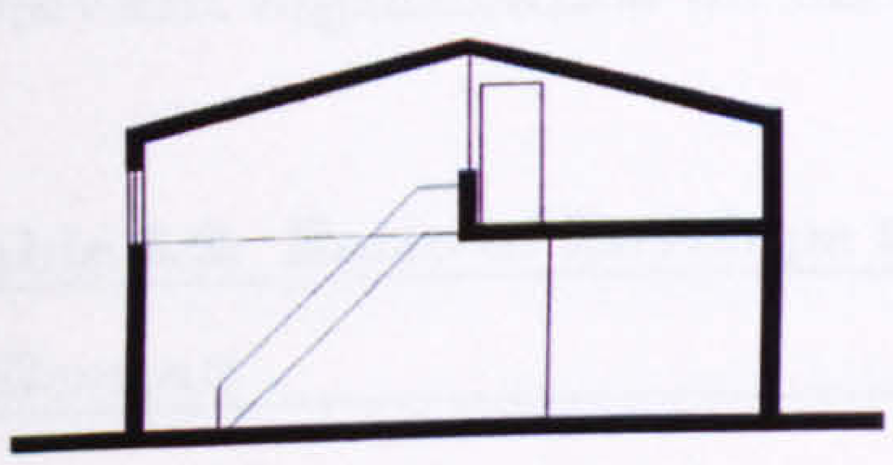
This two-story building of 240m^2 was completed in the summer of 1993 and has been designed mainly for residential use, however, the entire the first floor, an open plan area of 120m^2, was destined to fulfil office functions, leaving the ground floor for the domestic purposes. The office area is divided into two zones, one 20m^2 room for the management and an area of 100m^2 for open space office.



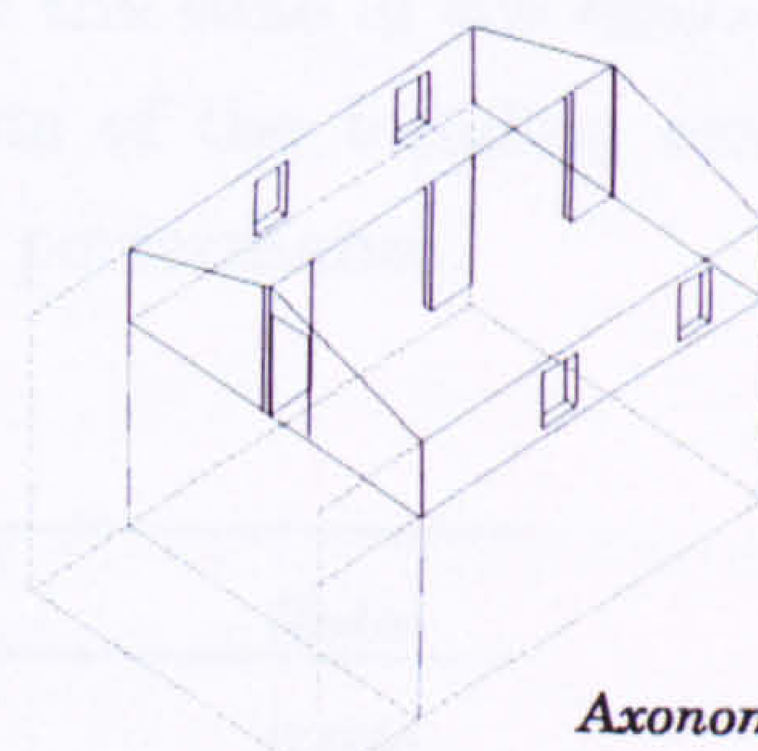
Plan



Wall Section



Section



Axonometric

Internal View

Table 5.1: Building Room Data - Huelva

Elements	*Area (m^2)*
floor	99
glazing	3.6
openable	1.49
internal surfaces	286
external surfaces	144
room volume	219.9 m^3

5.3 Building 1: *Huelva*

The construction is typical of the area: hollow brick masonry walls, concrete slabs for the intermediate floor and clay tiles on a steel beam structure for the pitched roof. The internal walls are also hollow brick and all finishes are plastered and painted white on both sides. Table 5.1 summarises the room data.

5.2.3 Environmental Features

The rectangular shaped plan of the building has its main long axis oriented north-south, thus, the longer facades are exposed to the sun mainly during the morning and afternoon. The windows are not externally shaded, however, internal blinds are used on each window for this purpose. One of the main features of the room is the small ceiling height respect to the floor area especially at the perimeter walls which are only about 1.60 high while at the centre of the room it measures 2.20 m. This shape results in a room with a large floor area but a relatively small volume. A 50 mm layer of polystyrene provides roof insulation but the rest of the building envelope is uninsulated. The internal surfaces of walls, partitions and ceiling are all painted in white and the flour is light red. The external surfaces finished with mortar and plaster were still unpainted at the time of the measurements. Table 5.2 provides additional information on aspects of the building envelope which have a relevant significance on its environmental performance.

Table 5.2: Ratio of Envelope to Floor Area

Elements	*Ratio*
glazing / floor	0.030
opening / floor	0.015
mass surface / floor (internal)	2.89
mass surface / floor (external)	1.45

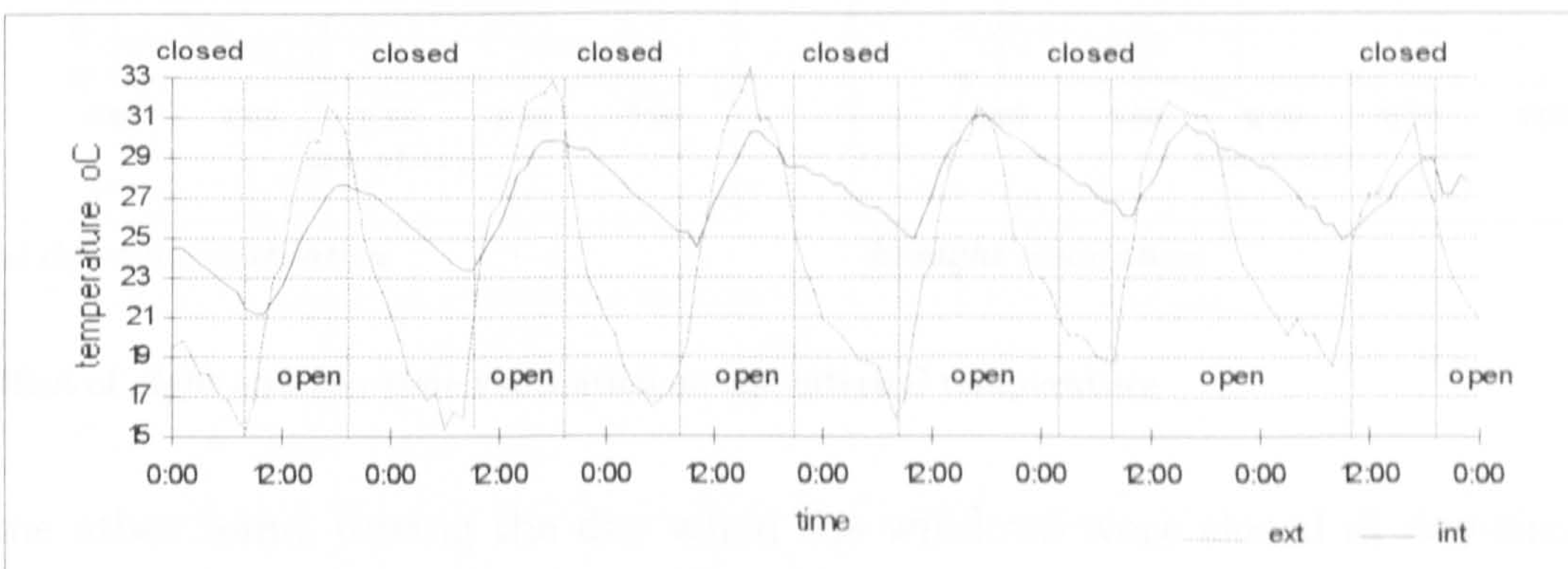
Values calculated for the office area only.

5.2.4 Thermal Monitoring Experiments

The experiments were carried out in the open office area on the first floor for a duration of 7 days. The external temperature recorded shows agreement with the local average weather data for that period although it was not possible to obtain the recordings from the meteorological office during those days. The external temperature profile maintains a fairly constant diurnal pattern throughout the week except in the last two days when the temperature swing was somewhat smaller than the previous five. The overcast conditions which dominated the sky during these two days may explain such reduction. The measurements recorded a gradual increment on the average internal temperature from 24 °C to 27 °C. during the first 36 hours of the experiments, (see graph 5.4). After this, the temperatures of the room stabilised at an average 27.5 °C, maintaining a diurnal temperature swing of approximately 5 K for the 7-day period.

5.2.5 Effect of Ventilation

Graph 5.4 shows the internal and the external temperatures for the overall monitoring period and indicates the times at which the windows were open and closed. From this graph, the effect of ventilation at different times of the day can be derived.

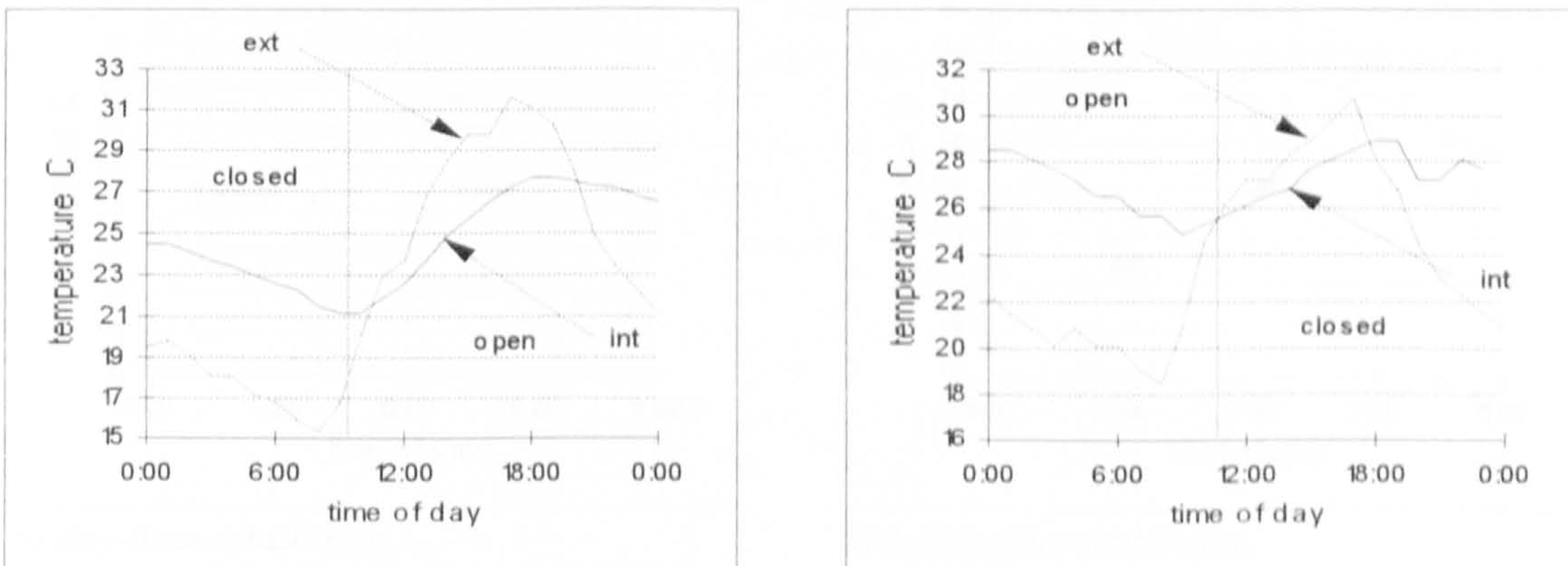


5.4 External and internal temperatures for the 7-day period. The vertical dotted lines indicate the times at which windows were closed and open.

The extent of temperature variations due to the ventilation in this building is not of great significance. This is largely due to the small window to floor area ratio of the room. With a room volume of 222 m^3, the total openable area of windows (1.49 m^2), is just sufficient to maintain good fresh air ventilation (2.5 ACH for a wind speed of 1m/sec, based on BREEZE simulations) but this rate is unlikely to bring significant variations to the thermal environment of the room. In addition to the small window area, this low ventilation rate is also due to the unfavourable window orientation with respect to the prevailing south-west wind direction.

5.2.5.1 Night Ventilation.

Graph 5.5 shows the effect of opening windows at night while keeping them shut during the day over a 24 hour period. As it can be observed, this action has little effect on the variation of the internal temperature. The difference between the external and internal temperature at night, when windows were fully open, is about 7 K. This is not very different from the situation observed during the previous nights when no ventilation was provided which clearly indicates that the proportion of incoming cool air is not significant. Apart from the small opening size of the room, as the wind blows slower at night, the air change rate may well be reduced at least by half the above figure at these hours.



a) day-time ventilation *b) night ventilation*

5.5 Effect of night and day-time ventilation on the internal temperature

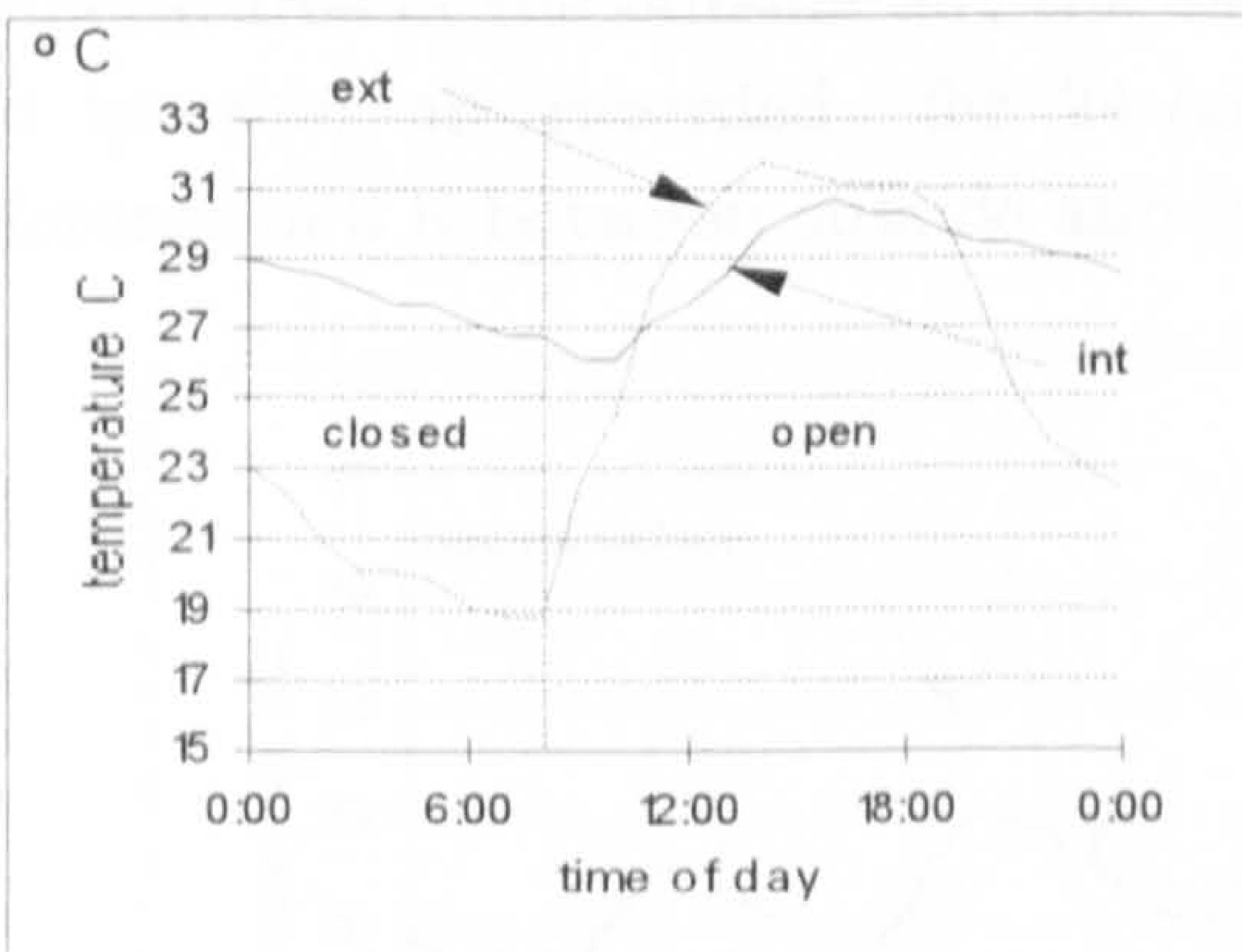
On the other hand, during the day when the windows were closed at day-time and open at night, the internal temperature was lower than in the previous days when the room was being ventilated at day time. This suggests that if greater night ventilation rates were provided the internal temperatures could have been reduced even further. However, this temperature reduction is unlikely to have been solely the effect of night cooling since the outdoor temperature that day was also lower than in the previous days.

5.2.1.2 Day-time Ventilation

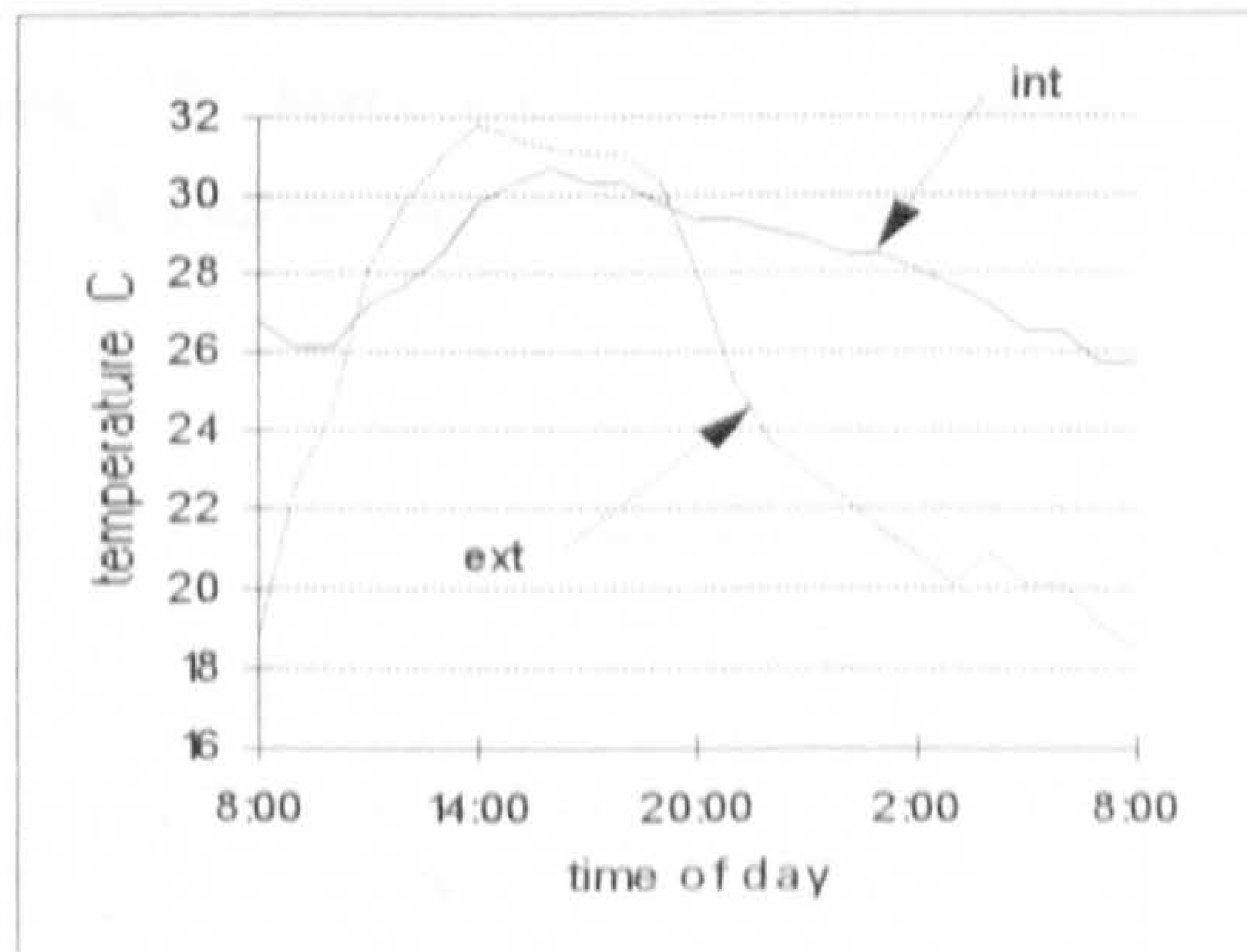
Another indication of the small effect of ventilation on the internal temperature was provided by the graph showing the effect of day-time ventilation . As the windows were open when the outside temperature rose above the inside's, the air change rate obtained in the room was unable to reduce the difference between the external and the internal temperatures. As a result, the internal temperature was kept below 28 °C even when the external was over 31 °C.

5.2.1.3 Continuous Ventilation

Even when the maximum external temperature dropped by more than 3 K the day when windows were left open continuously for 24 hours, there was no significant variation on the internal temperature curve, highlighting once more the moderate effect of ventilation on the thermal environment of the room.



a) day-time ventilation

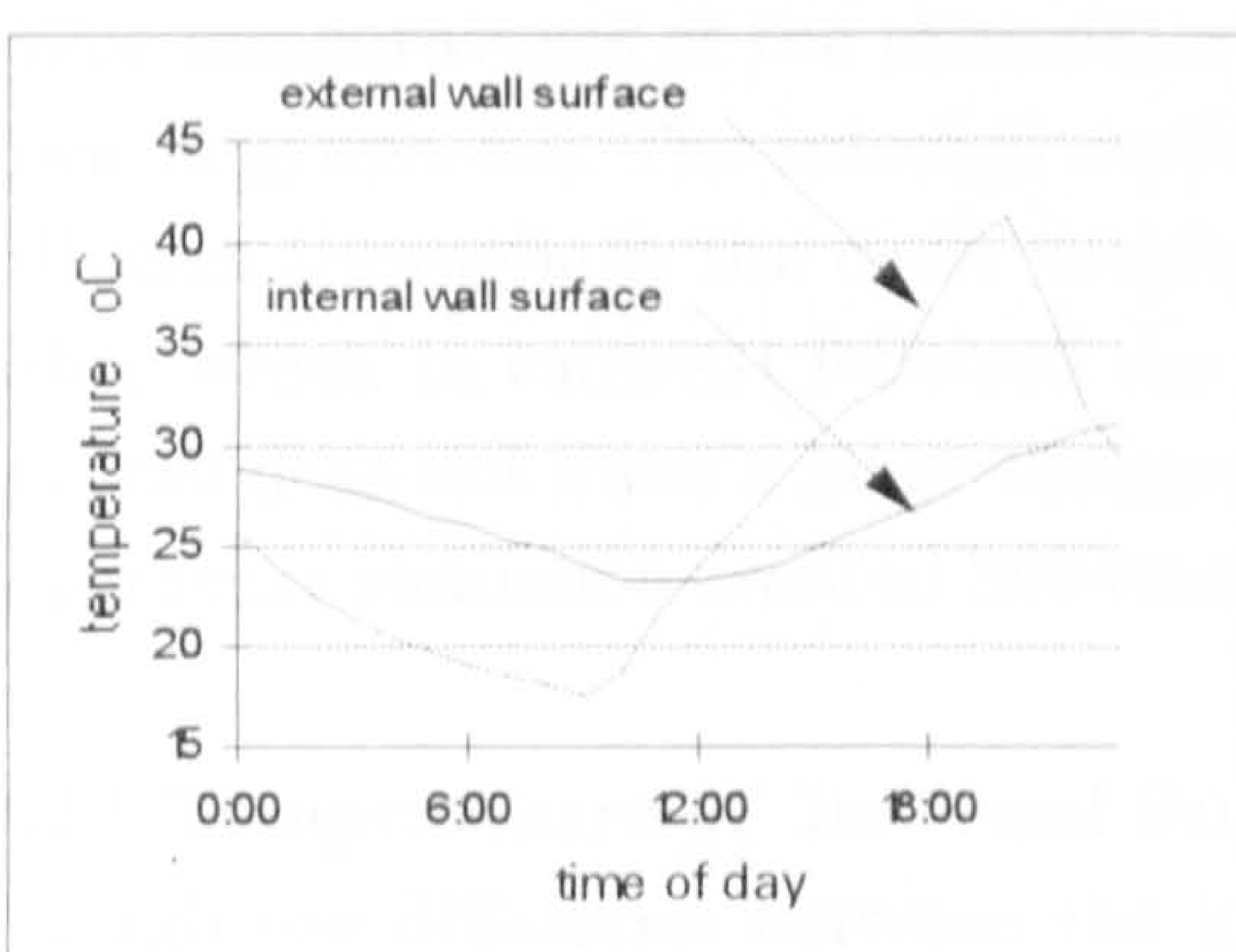


b) continuous ventilation

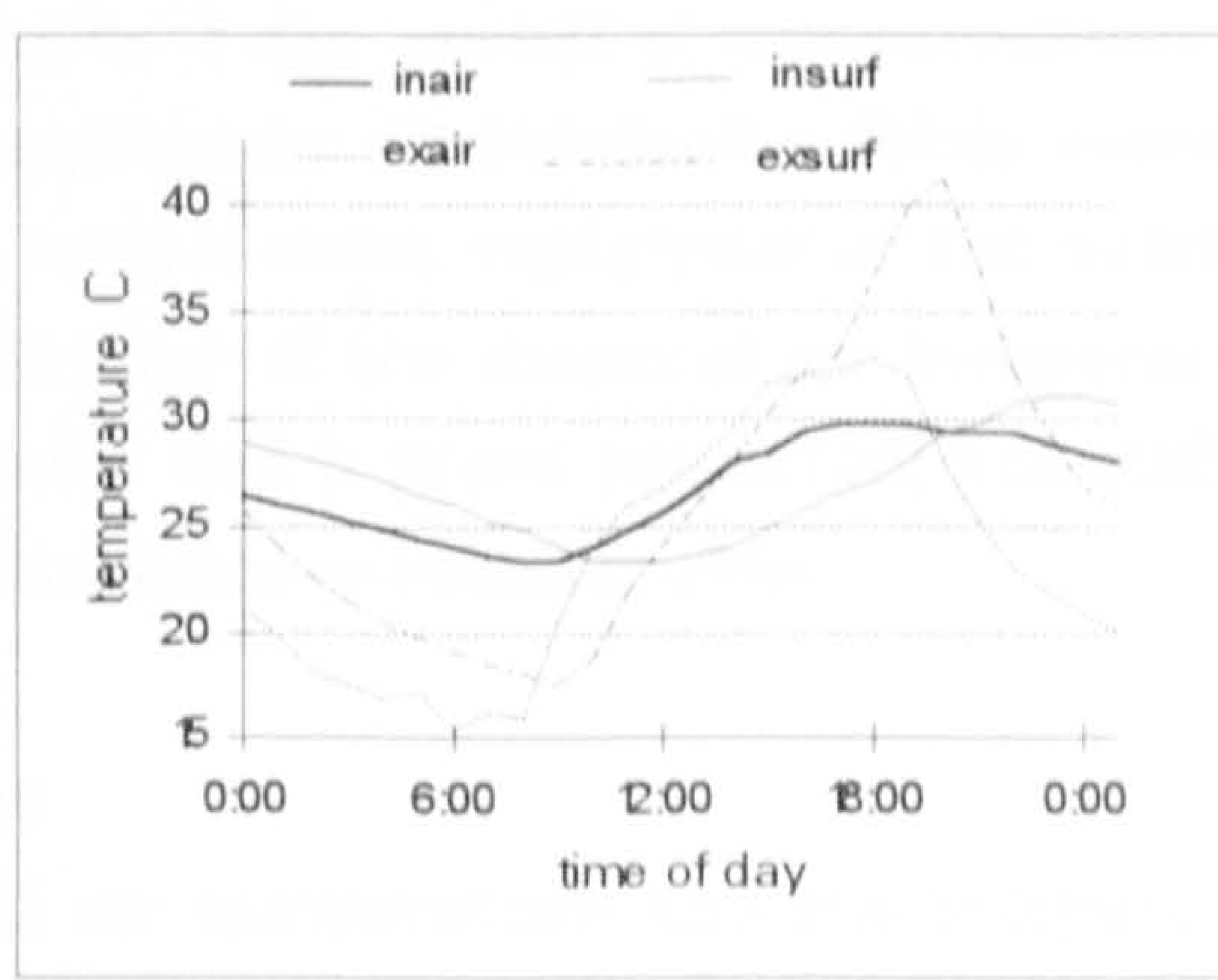
5.6 Effect of day-time and continuous ventilation on the internal temperature.

5.2.2 Effect of Thermal Mass

The 0.28 m thick masonry wall used for the experiment, has no insulation and is constructed 120 mm x 240 x 60 mm perforated bricks with plaster finish on both sides as shown in the wall section in 5.3.



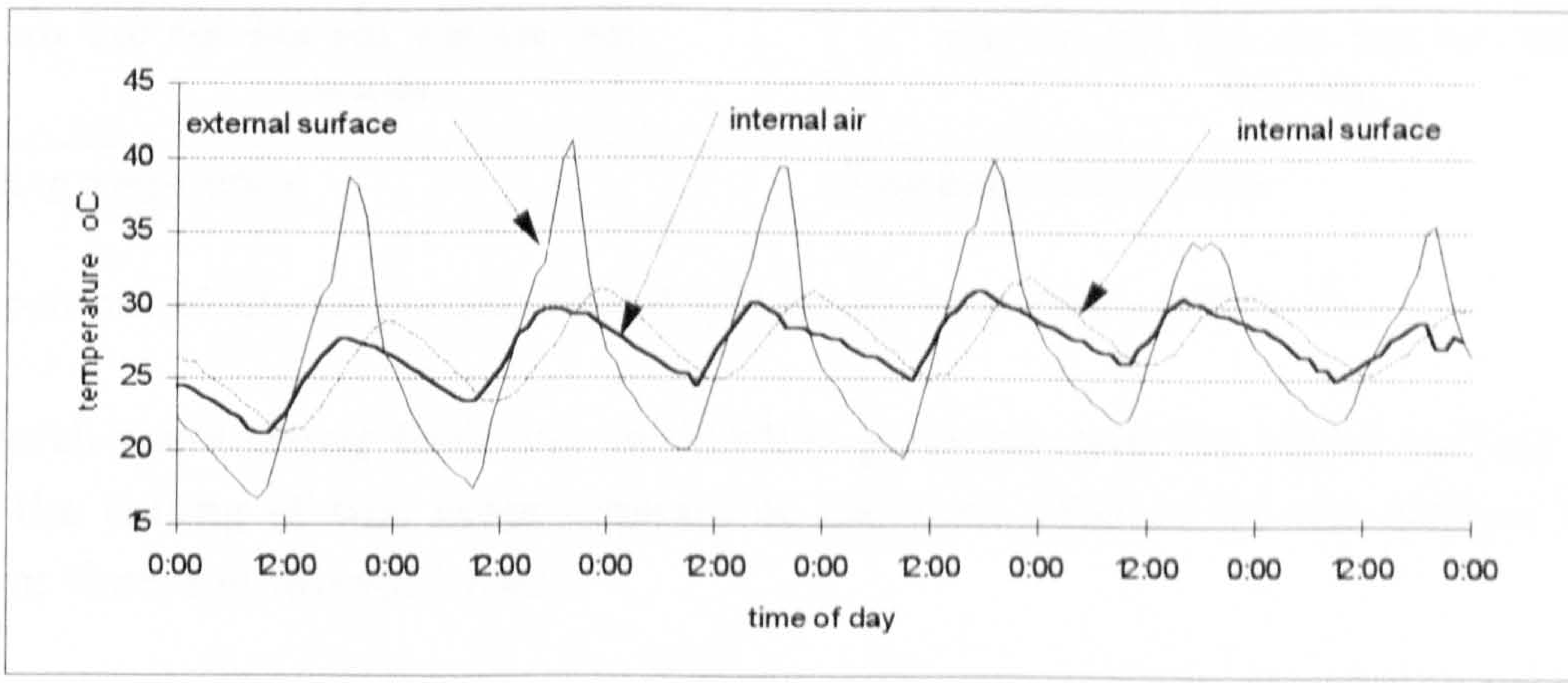
a) wall surfaces



b) air and wall temperatures

5.7 Temperature characteristics of external wall

The measurements of the external wall surface were carried out on the west facing wall, firstly, because it provided the larger exposed area to the external environment and secondly, because the otherwise preferred south-facing wall is not in direct contact with the room used for the experiments. As there are no obstructions on the surroundings of the building, this wall was completely exposed to the sun, from about 1:00 PM until the sunset around 9:00 in the evening. As to the internal wall surface, the temperature fluctuation at a rate of approximately 6 K during the 24 hour cycle is fairly constant during the 7-day period. For its location, this surface is not directly affected by the airflow of the room. Graph 5.7b shows the simultaneous temperatures of the outside air, the external wall surface, the internal wall surface and internal air recorded for 24-hour cycle. It indicates an air temperature difference of 3 K between outside and inside and a time lag of approximately 1 hour.

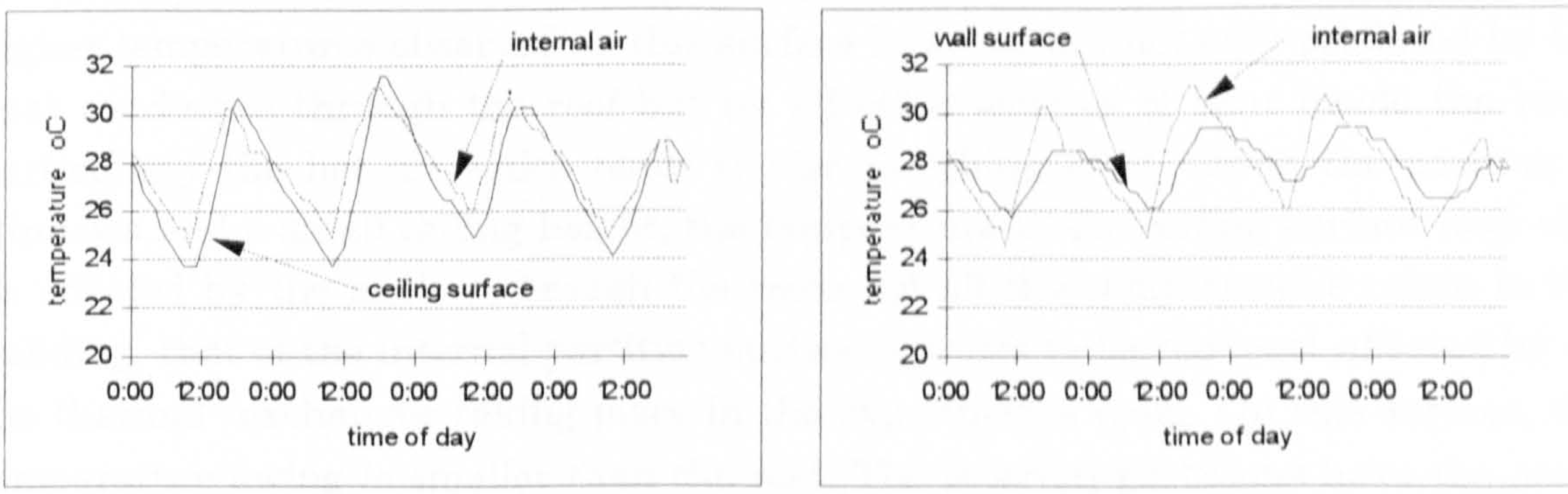


5.8 External and internal surface temperatures of envelope wall.

Meanwhile, the maximum temperature difference obtained between the internal and external surfaces is about 10 K with an approximate time lag of 5 hours . The surface temperatures of the external wall for the 7-day period of measurements are shown in graph 5.8. The internal surface temperature maintained a fairly constant oscillation throughout the cycle despite the temperature variations of the external surface which in contrast followed the fluctuations of the external air temperature. This wall does not have a large thermal capacity and it is not insulated, but still the temperature reduction created between both surfaces is considerable.

5.2.2.1 Temperature of Internal Surfaces

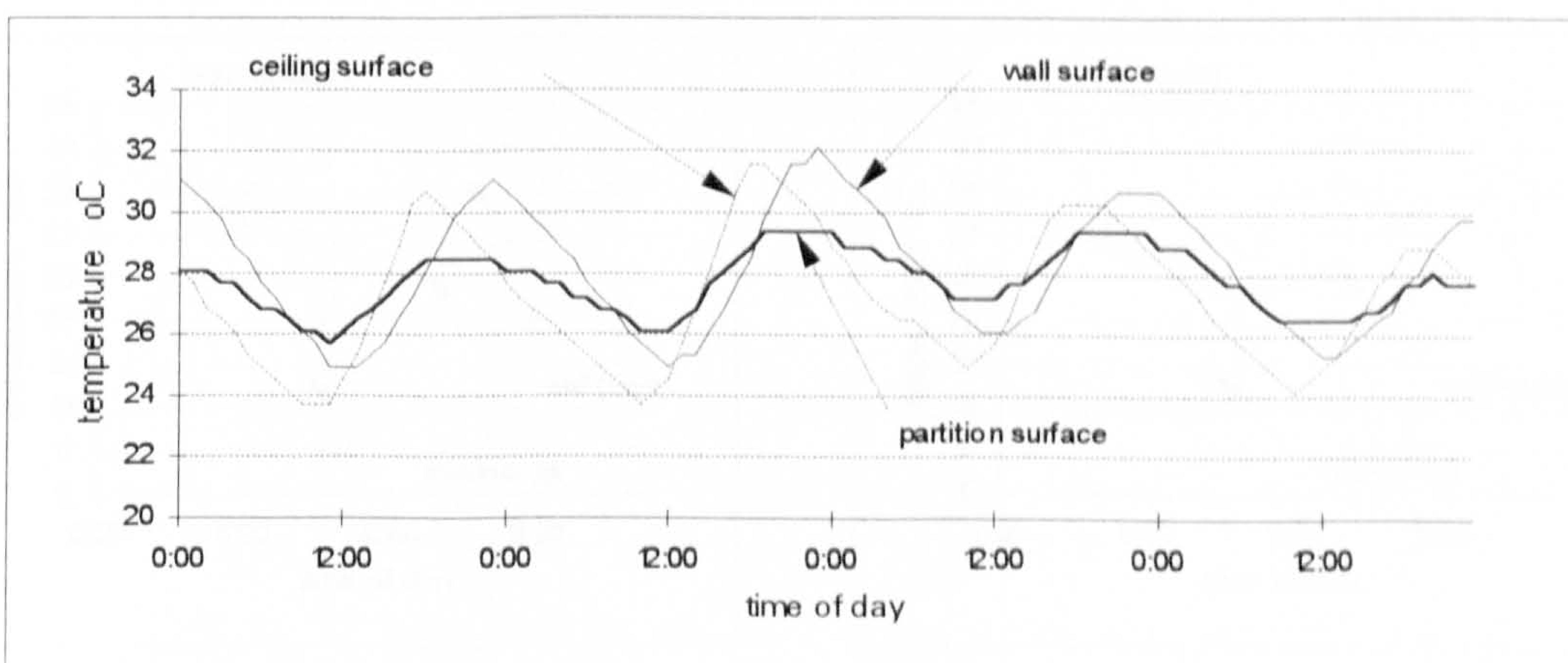
Although the difference between the internal air temperature and the temperature of the internal wall surface is not large, it is indicated that the air is constantly kept somewhat cooler than the wall surface. The temperature difference between these two is around 1 K for the entire cycle as shown in the graph 5.8. However, in the evening when the air temperature begins to drop, the temperature of the wall surface is still rising as heat is travelling through the external wall. Graph 5.9 relates the temperatures of the inner surface of the roof with the internal air temperature. Like the inner wall surface, the ceiling surface rises beyond the air temperature when they reach their maximum, however in this case the difference is less than 1 K, suggesting that the ceiling releases heat to the air at a quicker rate.



a) ceiling temperature *b)partition temperature*

5.9 Temperature of internal surfaces related with the air temperature of the room.

It is worth mentioning that due to window position, and the small ceiling to floor height the ceiling of this room appears to be more affected by the airflow through the room than the internal walls.

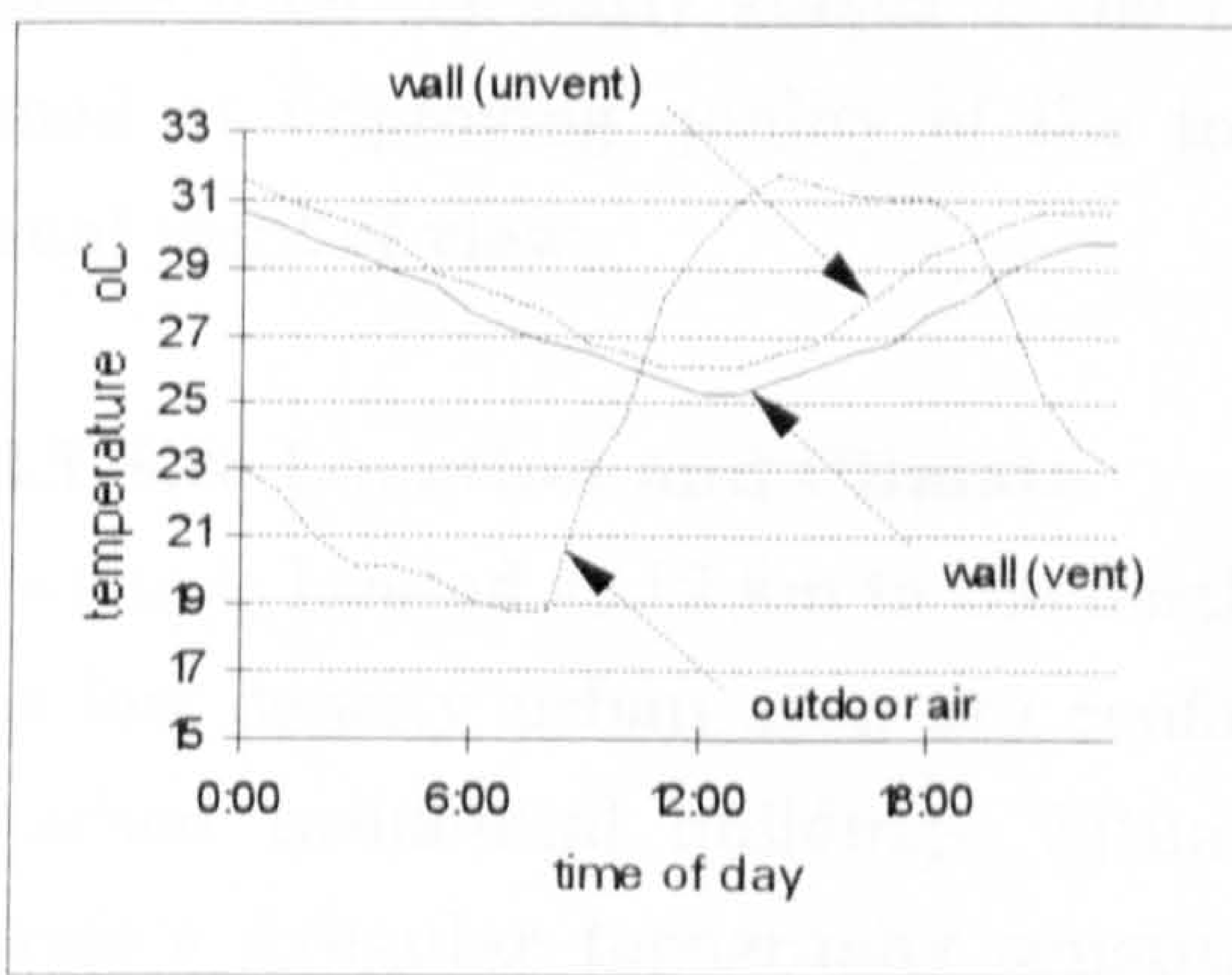


5.10 Temperature of wall, ceiling and partition surfaces for various days.

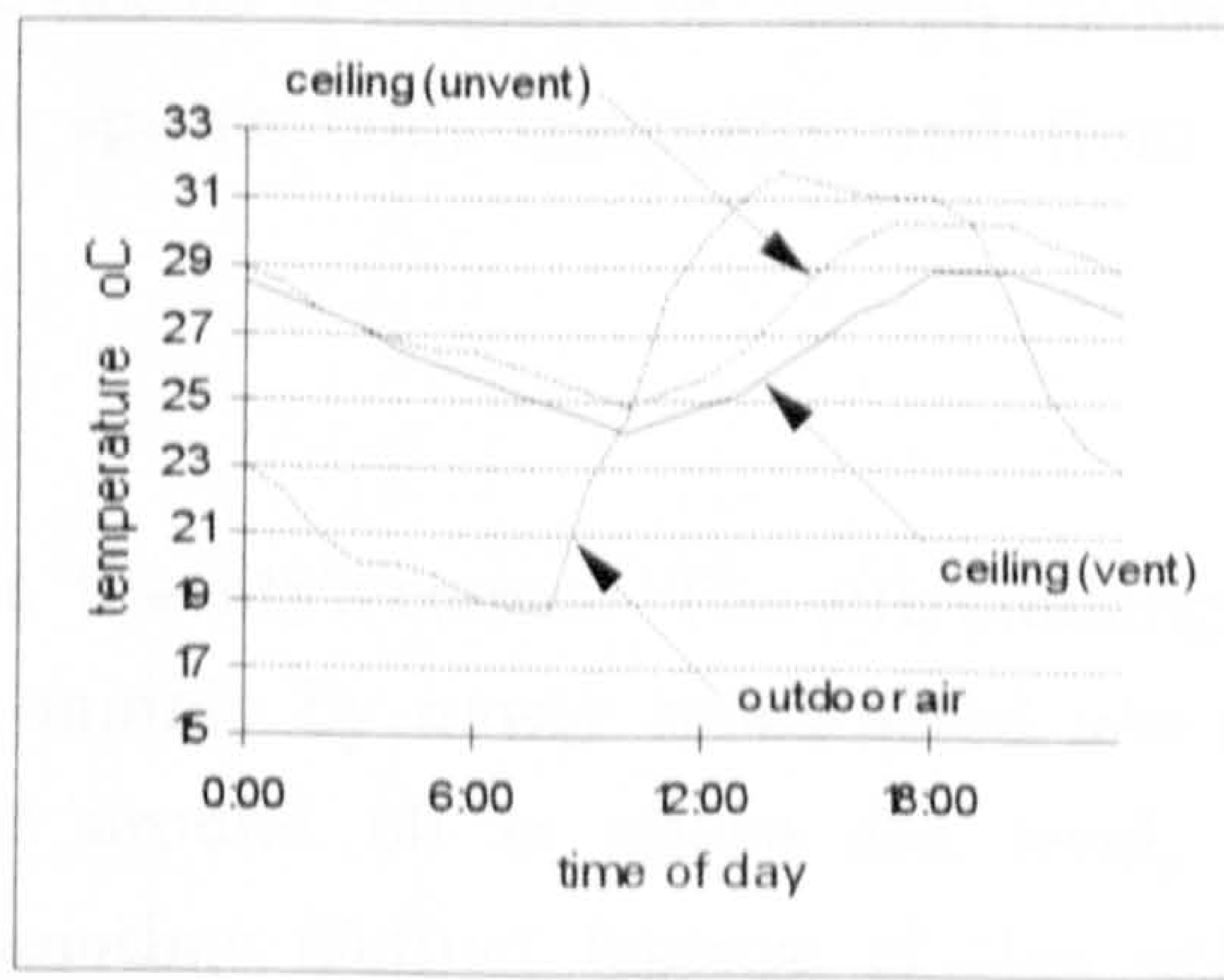
A greater temperature difference was observed between the air and the partition surface. As it maintains a more stable temperature variation, this suggests that the partition absorbs less heat throughout the day than any of the others elements measured. Of the three surfaces of the room, the partition maintained a smaller daily fluctuation and a slightly lower mean temperature. The temperature of the wall raised in various cases higher than that of the ceiling. This can be the effect of the insulation layer on the roof reducing the heat flow form the external roof surface. Additionally, because the wall area is significantly smaller than the ceiling, (mass to floor ratio of 0.15 compared to the ceiling MFR of 1), the heat diffusion within the wall surface occurs at a quicker rate elevating its surface temperature above that of the ceiling. Despite the insulation layer on the roof, the daily variation of the temperature of the ceiling surface is greater than that of the wall surface. The higher temperatures observed on this surface however are not only produced by the heat conducted through the roof but by all other sources of heat inside the room particularly the hot air which tends to rise to ceiling level. Given the position of windows and a small ceiling height, the temperature of the ceiling surface may also be affected by the airflow through the room. Of all the temperatures taken in the building, that of the internal partition surface appears to be the least affected by all the thermal exchanges taking place in the experiments room. On this surface, the temperature swing is smaller than the rest. The internal partitions have the same constructional characteristics as the external wall.

5.2.2.2 Internal Surfaces and Ventilation Air

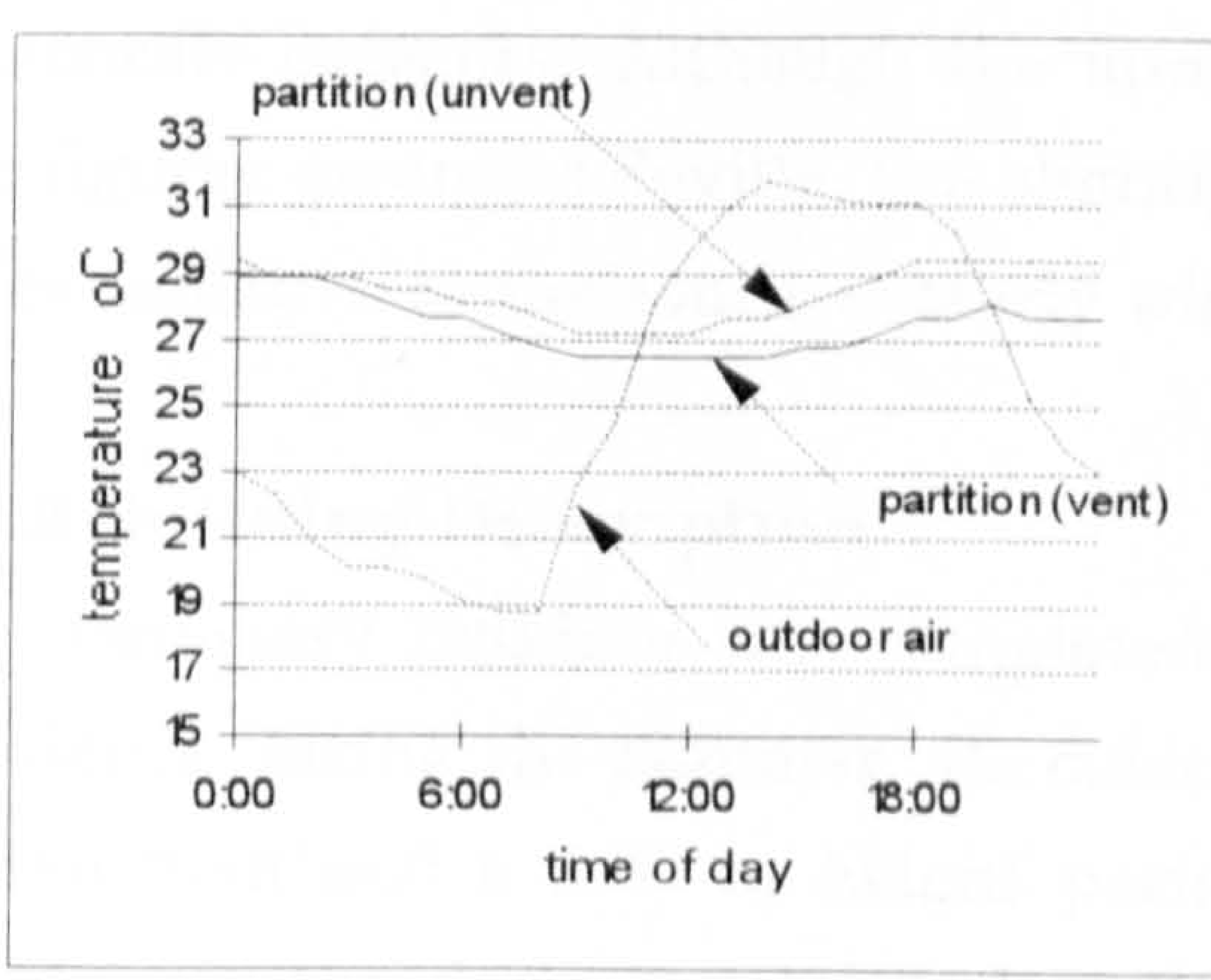
The following charts represent the thermal exchanges between the external air and the surfaces of the internal spaces of the building both for ventilated and unventilated situations.



a) internal wall surface



b) ceiling surface



c) *internal wall surface*

5.11 Effect of night ventilation on the temperatures of internal surfaces

The charts show the temperatures of the external air and the internal surfaces for both situations, when the room was ventilated and when it was unventilated. This can help to visualise the extent to which night ventilation is contributing to cooling of the building mass. The room surfaces curves indicate a considerable reduction of day-time temperature when the building has been ventilated the night before. However, when the building is cooling during night-time, the effect of night air entering the room shows a less pronounced effect on the surfaces. The internal partition measured is located at the centre of the room at 4.7 m from the window. The temperature of this surface was less affected by the influence of cool air entering the room. Its fluctuation (2 K) is smaller than that of the external wall and the response of temperature change with respect to the external temperature is quicker, (4 hours compared to 9 hours of the wall).

5.3 Case 2: *SALTERAS*

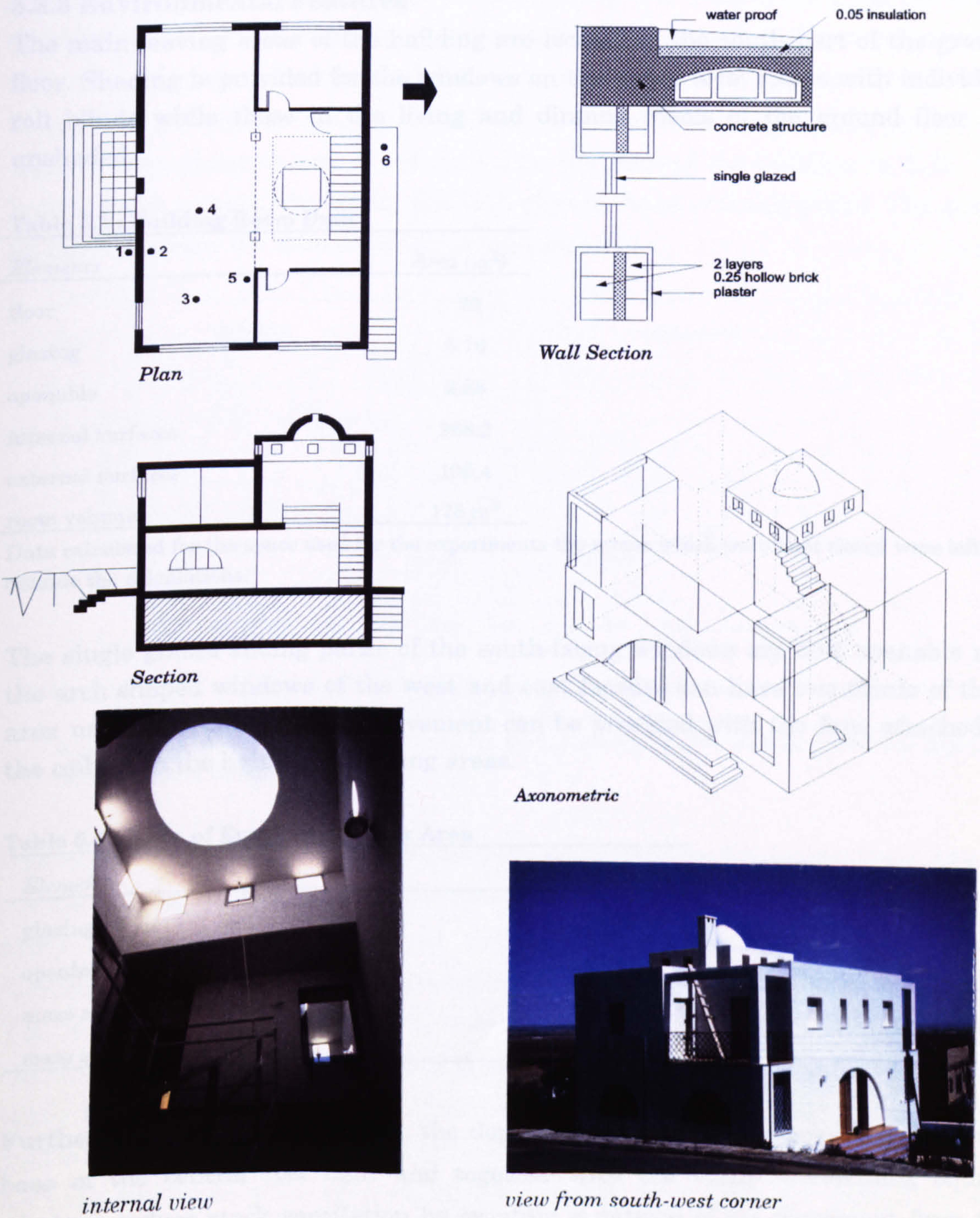
The second building selected for the field experiments is situated in the growing residential urbanisation of Salteras in the outskirts of Seville. As part of the brief, the design of the building was given particular consideration to environmental aspects from the early stages of the project taking a number of design measures aimed at improving quality of the internal spaces both thermally and from the visual point of view.

5.3.1 Site Location and Climate

The site is located at 12 km to the north-west the city's centre. The surroundings of this low density urban area are conformed mainly by newly constructed low rise detached residential buildings. Situated at around 50 m above sea level, the terrain's irregular topography constitutes another distinct feature of this urban area. The micro-climate of this location falls under the region's Mediterranean temperate category. Although the annual mean temperatures are fairly similar to the figures given for Seville, the slightly higher altitude of this area, makes the site more sensitive to the south-westerly winds coming from the Atlantic.

5.3.2 Building Description:

The two-story building was completed in early 1993 and is used as a temporary residence during the summer. Its cubic symmetrical shape is made of an 12.00m x 8.00m plan and a 5.00 m height perimeter wall. A major design feature of this building is the dome constructed at the back centre the roof, which assisted by a series of small clerestory apertures around it, ensures good daylighting throughout the building's interior. Results of a detailed daylight analysis carried out for this building can be seen in [74]. The main structure of the building is constituted by solid brick masonry walls with a 50 mm layer of expanded polystyrene for thermal



5.12 Building 2: Salteras

insulation. The roof is a 400 mm reinforced concrete slab with an insulation layer and the dome is constructed with clay bricks and plaster finish on both surfaces. The building is constructed on a west-east sloped plot which allowed room for a basement level along the east end of the plan.

5.3.3 Environmental Features

The main leaving areas of the building are located in the south part of the ground floor. Shading is provided for the windows on the upper level rooms with individual roll blinds while those in the living and dinning rooms of the ground floor are unshaded.

Table 5.3 : Building Room Data

Elements	*Area (m^2)*
floor	70
glazing	5.76
openable	2.88
internal surfaces	268.2
external surfaces	106.4
room volume	175 m^3

Data calculated for the space used for the experiments the rooms which were kept closed were left outside the calculations.

The single glazed sliding panes of the south-facing windows are 50% openable and the arch shaped windows of the west and east facades can have two thirds of their area unclosed. Additional air movement can be provided with the fans attached to the ceiling on the living and dinning areas.

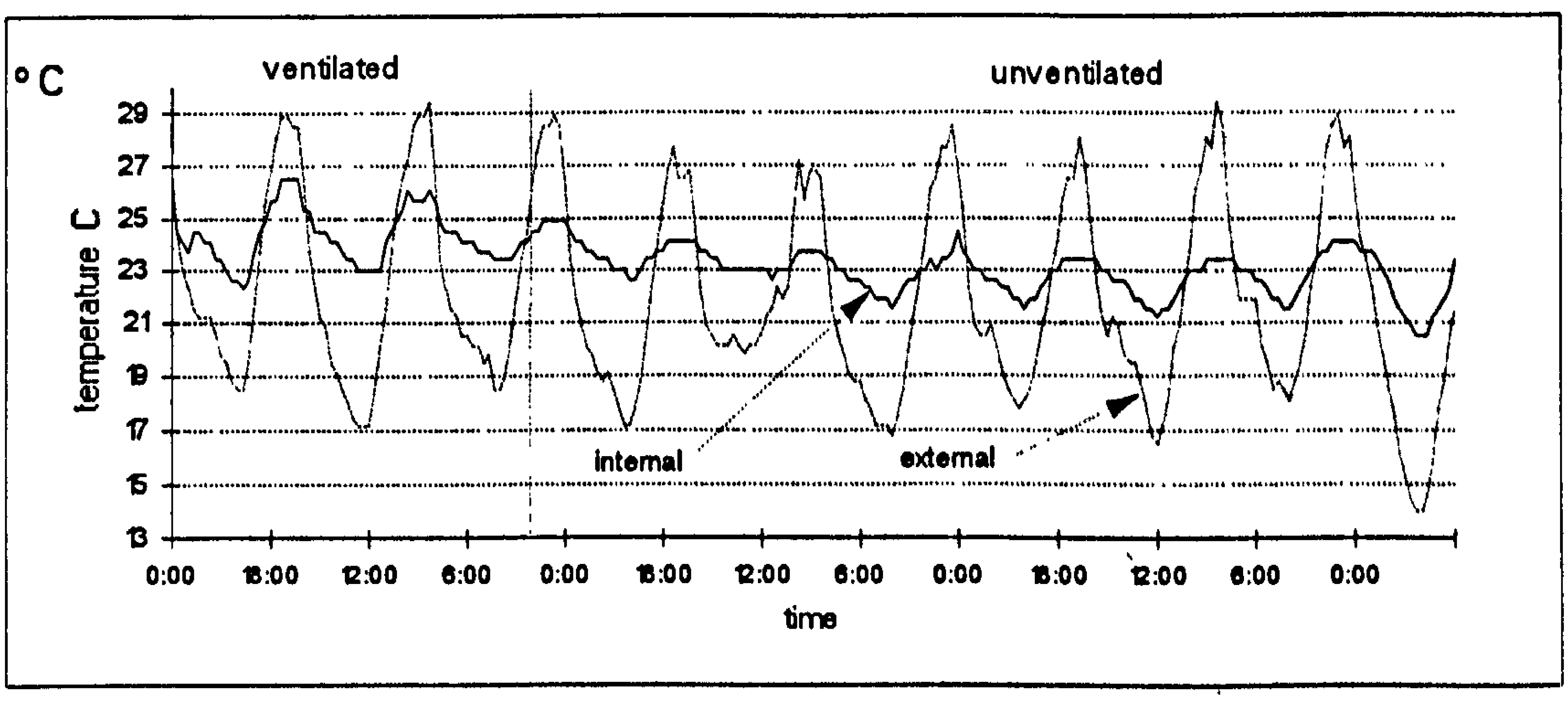
Table 5.4: Ratio of Envelope to Floor Area

Elements	*Ratio*
glazing / floor	0.082
opening / floor	0.041
mass surface / floor (internal)	3.03
mass surface / floor external	1.07

Further to its daylight functions, the dome on the roof has an aperture along the base of the central roof light and together with the other surrounding square windows induce stack ventilation by creating a pattern of air movement from the front windows across the building. The insulation layer of the envelope is located in the centre of the cavity wall and the solid clay bricks and plaster finish constitute the structure's main thermal mass. Table 5.4 summarises the ratio between the area of the building components and the floor area.

5.3.4 Thermal Monitoring Experiments

The ten-day monitoring program for this building was carried out from the 3rd to the 13th of September. The experiments included the recording of temperature data from the external and internal air, the external and internal surfaces of the south facing wall and the surfaces of internal partition and the ceiling. The location of the sensors throughout the room are shown on the plan of the building in 5.12. The building was occupied during the first 2½ days of the monitoring period. The graphs on the right show the data recorded by each sensor.



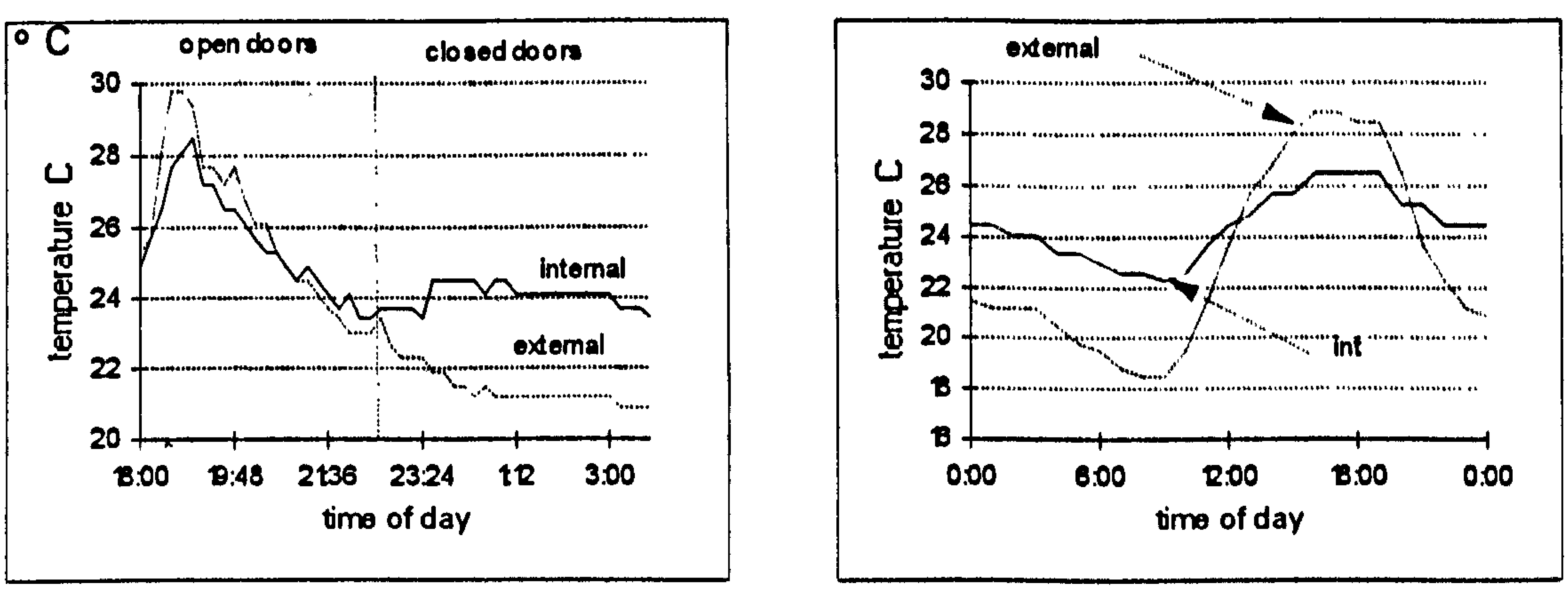
5.13 External and internal temperatures for the 10-day period. The vertical dotted line indicates the time when windows were closed.

The external temperature recorded corresponds closely to the temperature data of Seville for September. The temperature curve maintained except for two days, a fairly constant swing throughout the monitoring interval with an average temperature of 23 °C. The variations of the internal temperature oscillated between 1 K - 4 K. A gradual reduction of the mean temperature was observed as the days of the experiments progressed. The readings of the external surface temperature were taken from the south facing wall of the building. During the overheated period, this wall is exposed to the sun most of the day. The curves show a direct correspondence with the amplitude of the external air temperature though a larger fluctuation was observed.

5.3.5 Effect of Ventilation

The effect of ventilation on the internal temperature can be identified during the first 3 days of the monitoring period when the building was occupied, 5.13. The rest of the time the building was kept unventilated which allowed to isolate the effect of thermal mass. The window aperture to volume ratio of this building is large enough to maintain a ventilation rate above 30 ACH for a local average wind speed of 2 m/sec if all apertures are left open (from BREEZE simulations), and as shown in 5.14, this ventilation would cause a strong effect on the internal temperature. This graph shows the external and internal temperatures shortly after the sensors were installed when most windows and doors were temporarily open.

During that time, the anemometer recorded wind speeds at an average 2m/sec producing a room ventilation rate above 16 ACH. However, during the next two days when the building was occupied, the windows were only minimally open day and night supplying only an estimate 6 ACH, thus, reducing significantly the potential for convective cooling.



a) aperture open and closed *b) continuous ventilation*

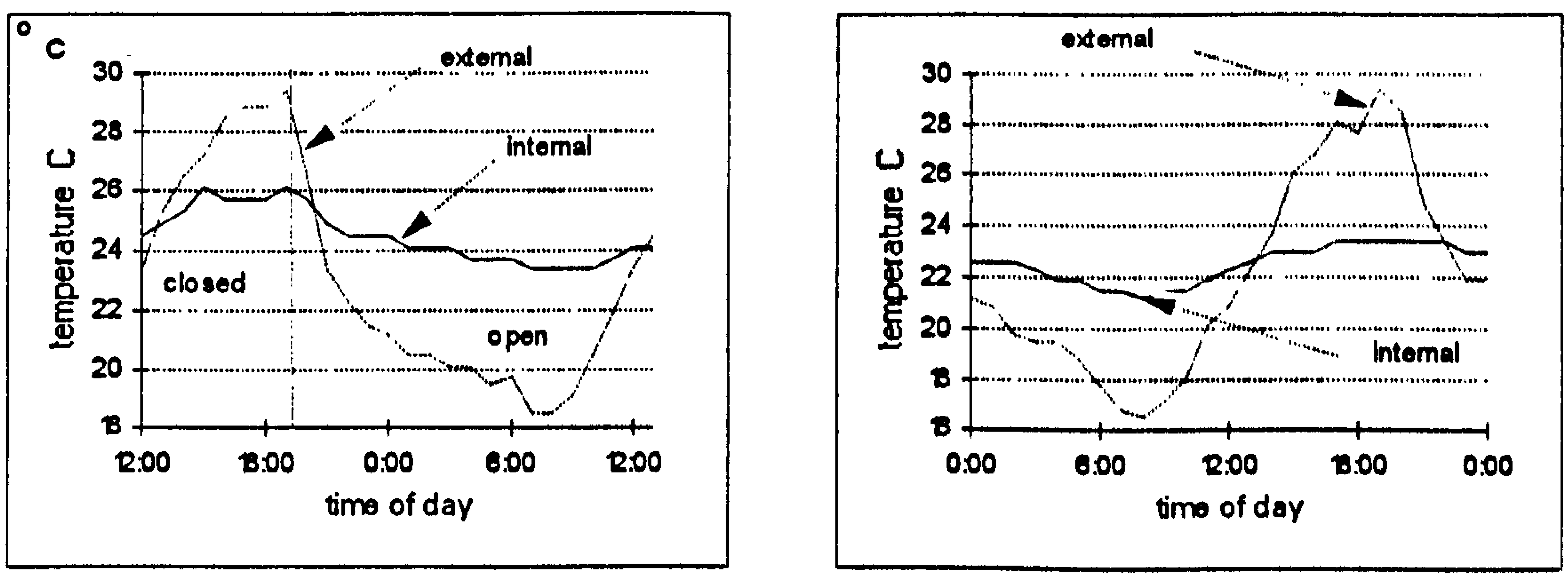
5.14 Effect of various window aperture conditions (ventilation rates) on internal temperature

5.3.5.1 Night Ventilation.

Graph 5.15 a isolates a 24 hour period when the building was ventilated at night. Note that although windows were not kept closed all the time during the day, it is clearly shown that the at the warmer hours when they were shut, the internal temperature ascent in progress was effectively interrupted. The conditions inside were maintained at a fairly constant 26 °C until the windows were open again when the outside air became cooler.

5.3.5.2 Unventilated

Even when the building was unventilated the internal temperature curve indicated a fluctuation of around 2 K 5.15 b. This is because the permanent aperture at the centre of the roof-light which reduces the air-tightness of the building as a whole, generates ventilation due to stack effect.

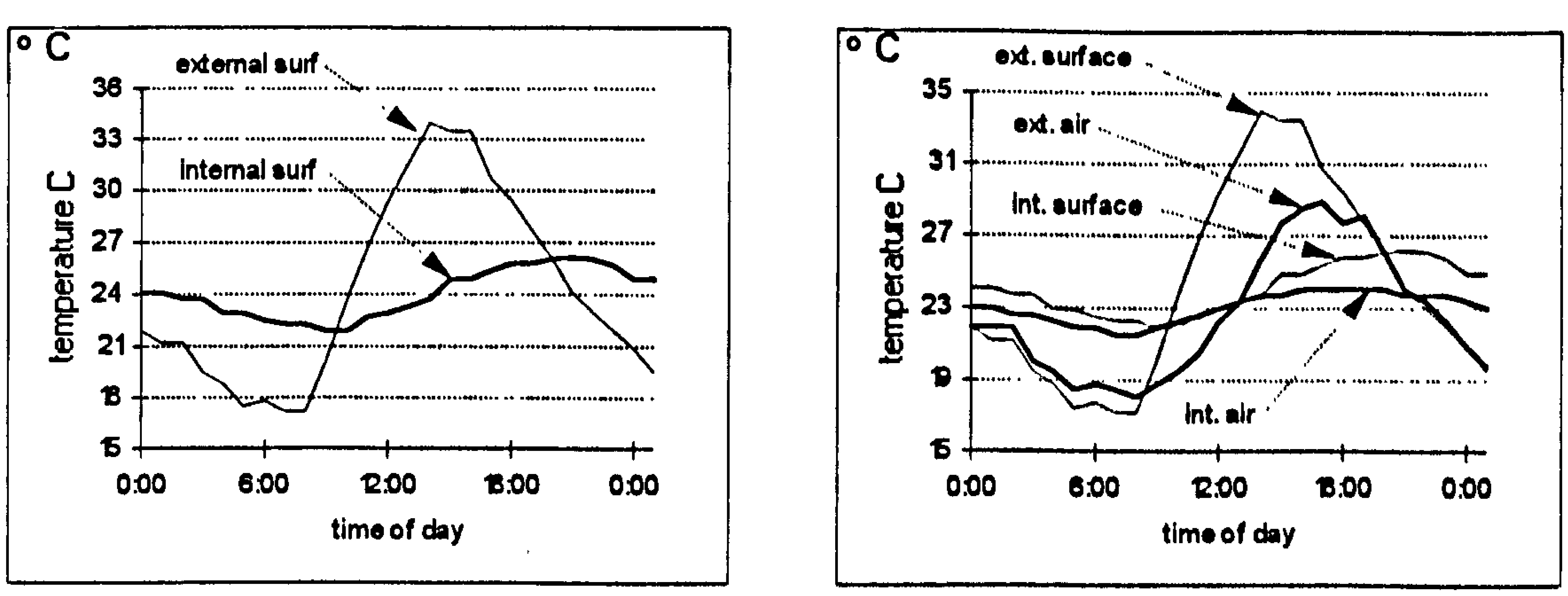


a) night ventilated *b) unventilated*

5.15 Internal temperature variations according to the effect of night ventilation

5.3.6 Effect of Thermal Mass

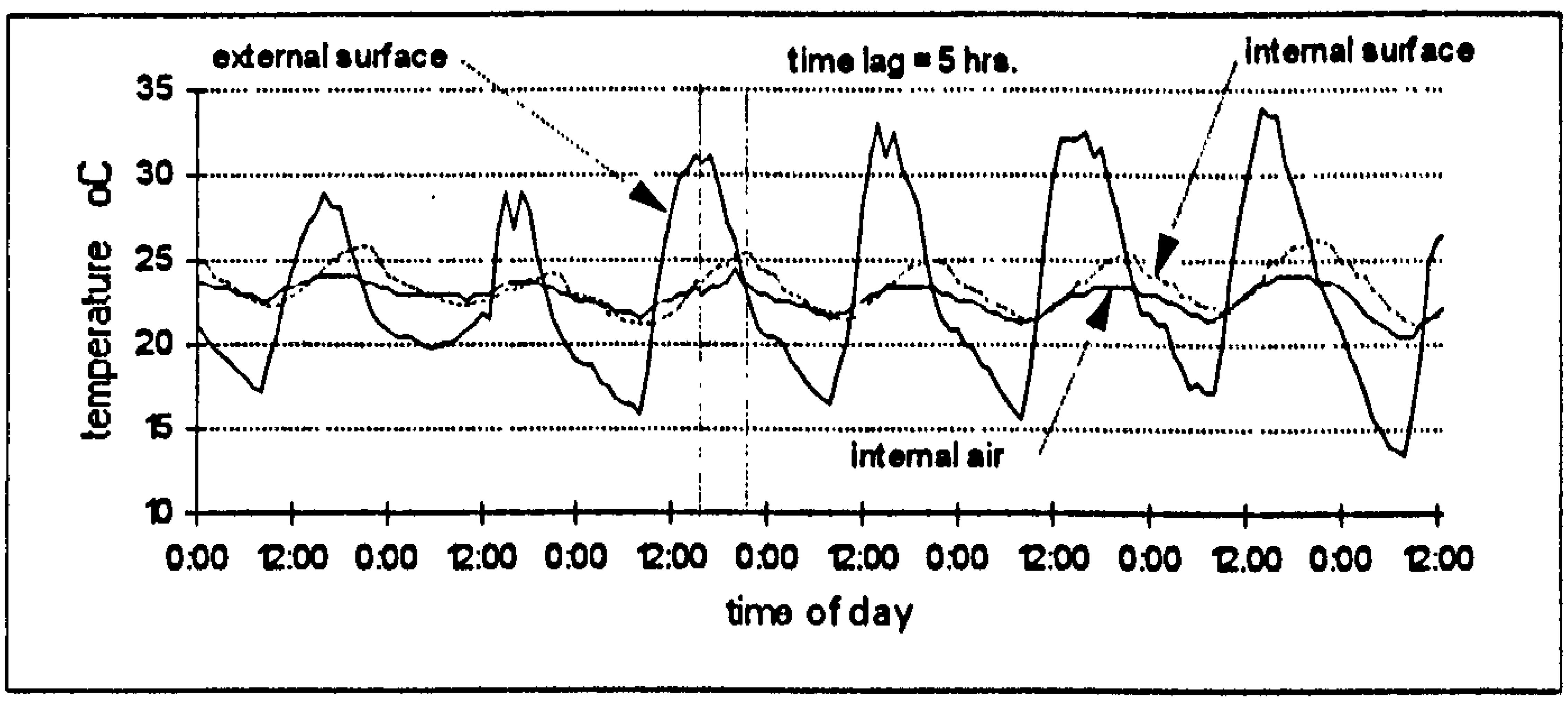
The fairly massive and insulated envelope of this building provided a rather consistent temperature curve throughout the 10-day interval of the experiments. The fluctuation of the internal temperature was maintained within 2 K during the unventilated period. Temperatures measurements of the wall, the ceiling and partition surfaces, provided the data for studying the effect of the building mass on the internal environment.



a) wall surfaces *b) air and wall temperatures*

5.16 Temperatures characteristics of external wall.

The temperature flow from the outside to the inside through the south facing wall of the building for a 24-hour cycle provides a good indication of the effect of the insulated wall on the heat flowing inside the building through the envelope, 5.16. This was carried out by recording simultaneously the external and internal temperature plus the wall's inner and outer surfaces. The maximum temperature difference observed between the outside and inside air of this building is around 5 K with a time lag of 1.5 - 2 hours, although the external surface often became over 10 K warmer than the internal surface with a time lag of 5 hours created by the building mass. The temperatures of the inner and outer wall surfaces for the 10-day period of measurements are shown in 5.17.

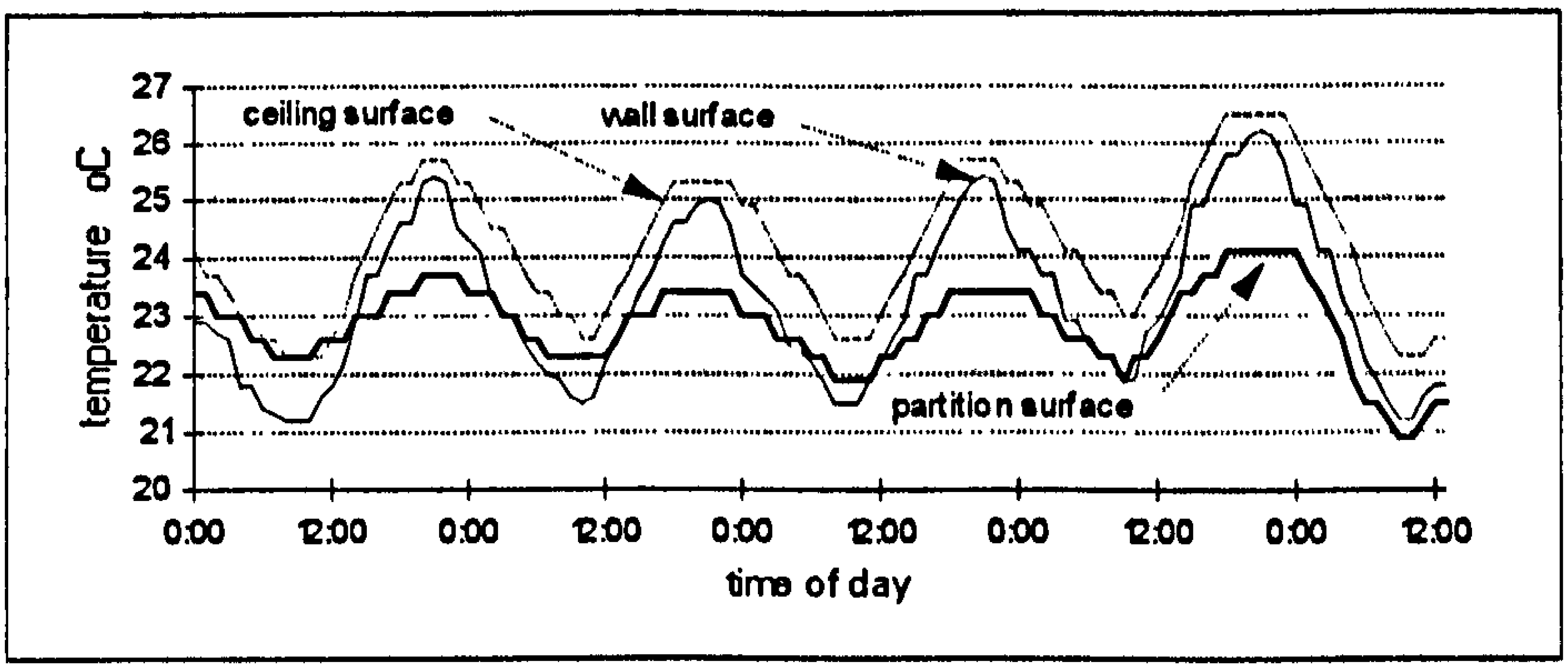


5.17 External and internal surface temperatures of the envelope wall.

An indication of the effect of the conductance and heat storage capacity of this wall on the inside space can be observed by the reduction of the temperature swing from 10 K on the external surface to 4 K on the internal surface. The maximum temperature difference registered between the internal and external surfaces is 8 K, when the external surface reached 34 °C.

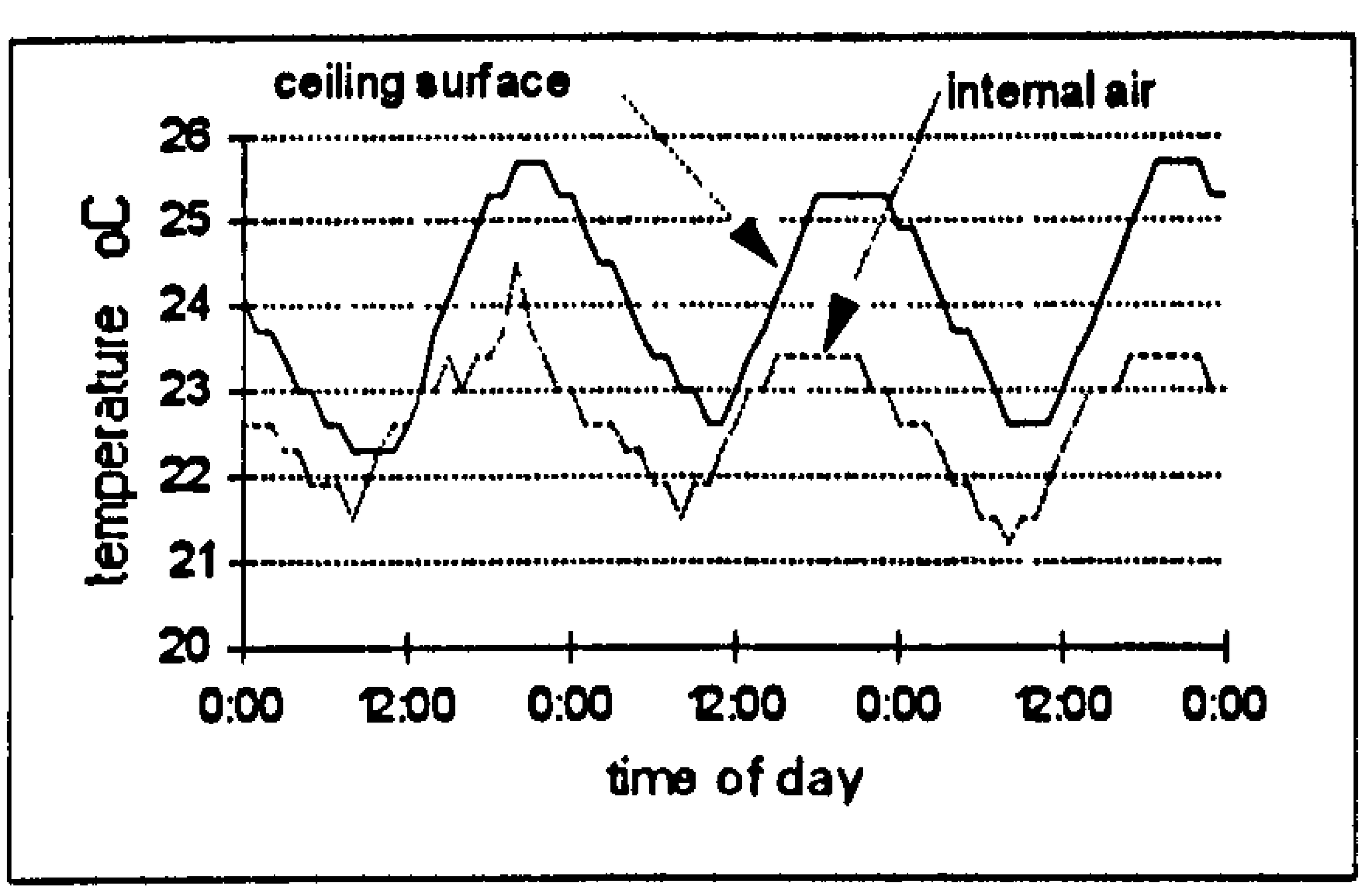
5.3.6.1 Temperature of Internal Surfaces

The temperature of the internal surfaces of the envelope wall was measured by placing the sensor at 1.00 M. from the floor on the south facing wall. Although there are windows on this wall, its internal surface was not directly exposed to the incoming air. The ceiling surface measured is an inter-floor element with virtually no temperature difference between rooms. The sensor for the partition wall was placed at about 1.00 M. from the floor. This partition wall is located at about 3.00 m distance from the window on the opposite wall. The inner surface of the envelope wall remained at high temperatures than the internal air for most of the day-time hours. The difference ranged between 1 K to 2 K. At night these two temperatures became closer, the surface falling around 1/2 K lower in most cases. On the ceiling surface the fluctuation of temperature is similar to the internal wall surface around 3 K. Graph 5.19 shows the temperatures of the inner surface of the ceiling and the internal air over a period of three days.

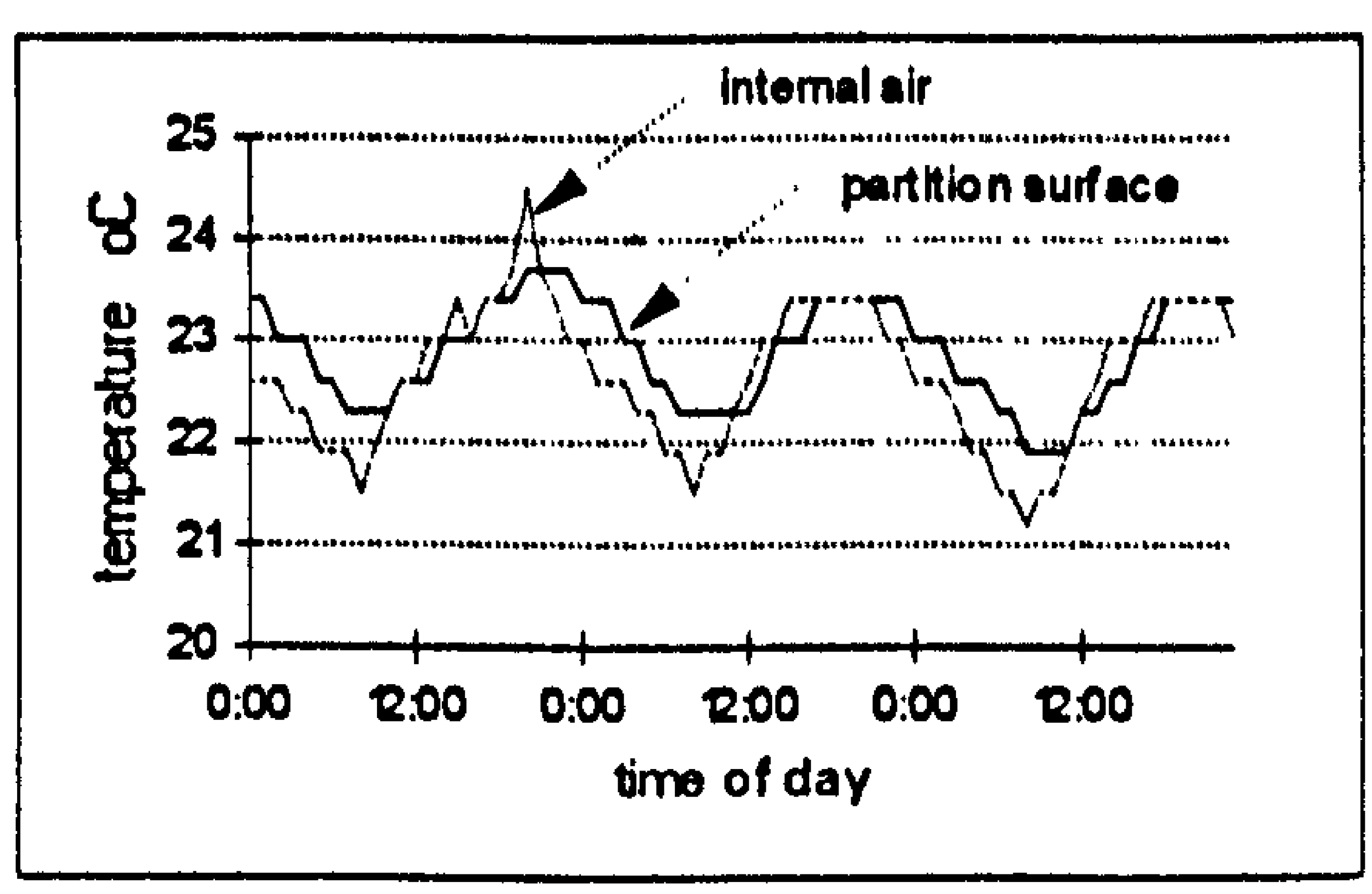


5.18 Temperature of internal surfaces

The ceiling surface was recorded always warmer than the internal air and the other two surfaces. Not even at night-time or/and when the building is ventilated, this situation is altered.



a) ceiling and internal air temperatures



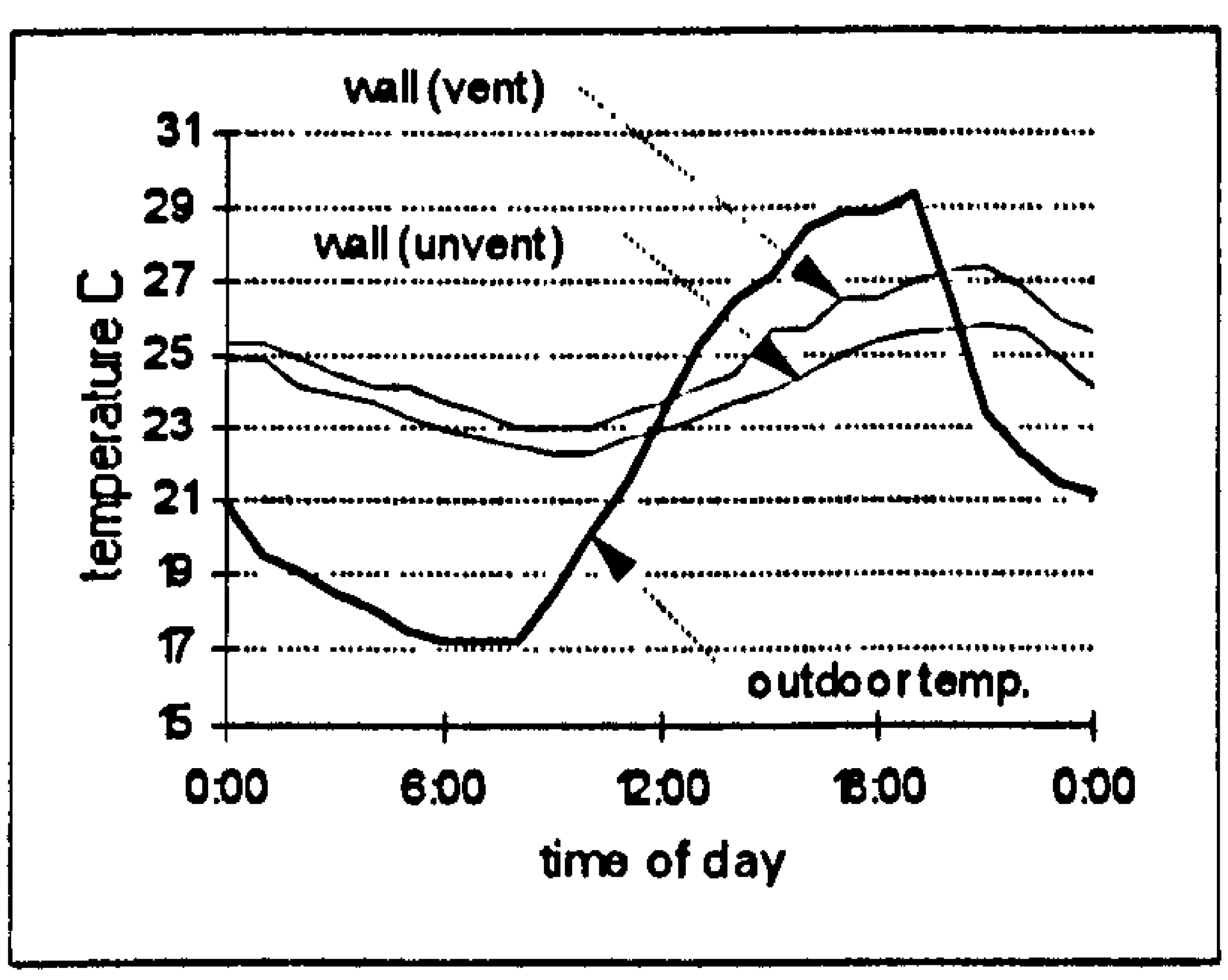
b) partition surface and internal air temperature

5.19 Temperature of internal surfaces plotted with the internal air temperature

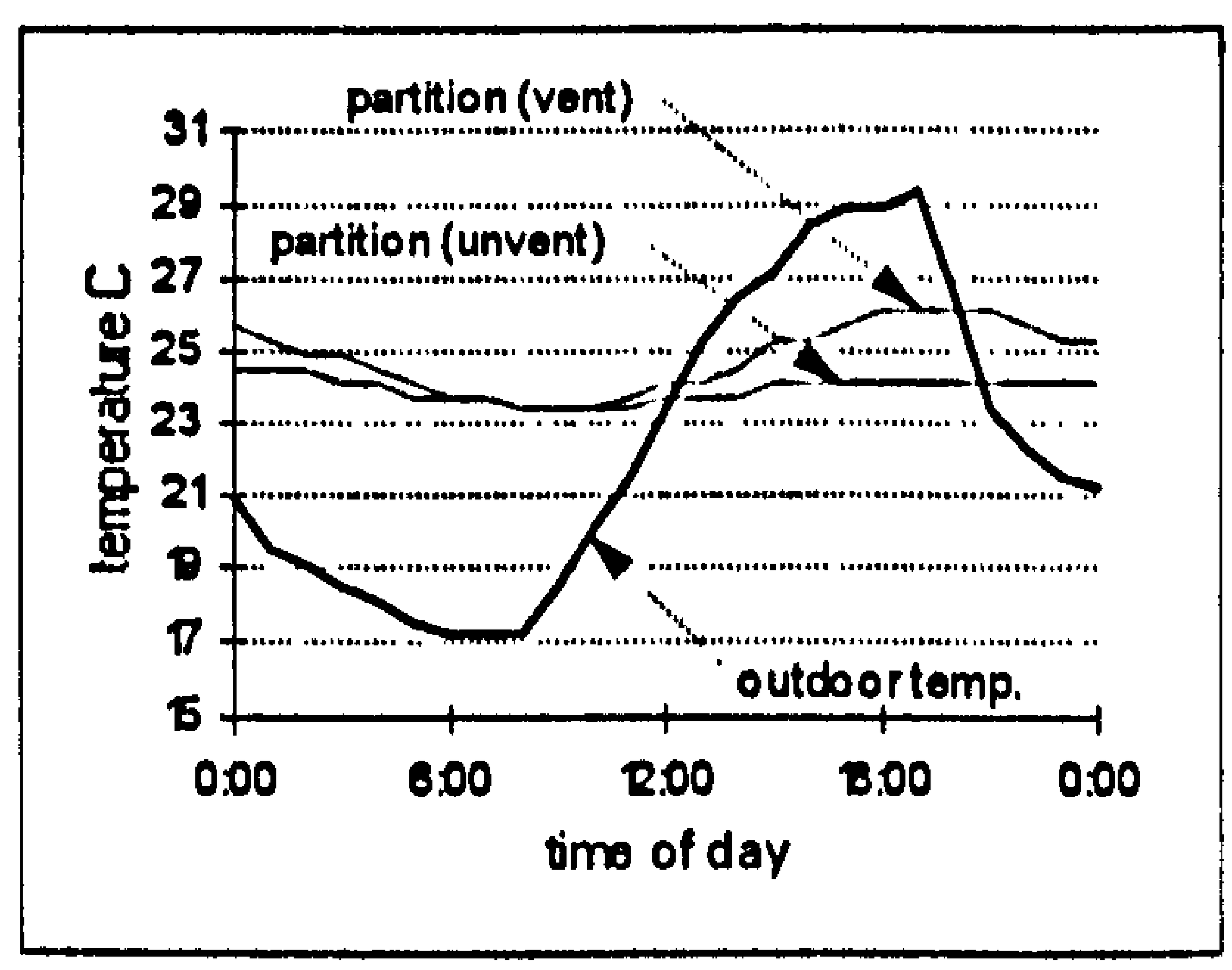
The internal air temperature at night was usually half way between the external temperature and the temperature of the ceiling. This probably indicates the low effect that night convection was having on heat loss of the building mass especially the ceiling which appears to have absorbed most of the room's gains. This correlates with the results of building 1 in Huelva. The temperature of the internal partition surface was maintained close to the internal air temperature curve. Graph 5.19 illustrates these curves over a period of three days although the pattern is repeated during the whole period of experiments. This may indicate that this wall was absorbing less heat than the surfaces of the ceiling and the external wall and that despite the insulation layer of the external wall, some heat gains were being conducted through the building envelope. These conditions were also present during the ventilated period.

5.3.6.2 Internal Temperature and Ventilation Air

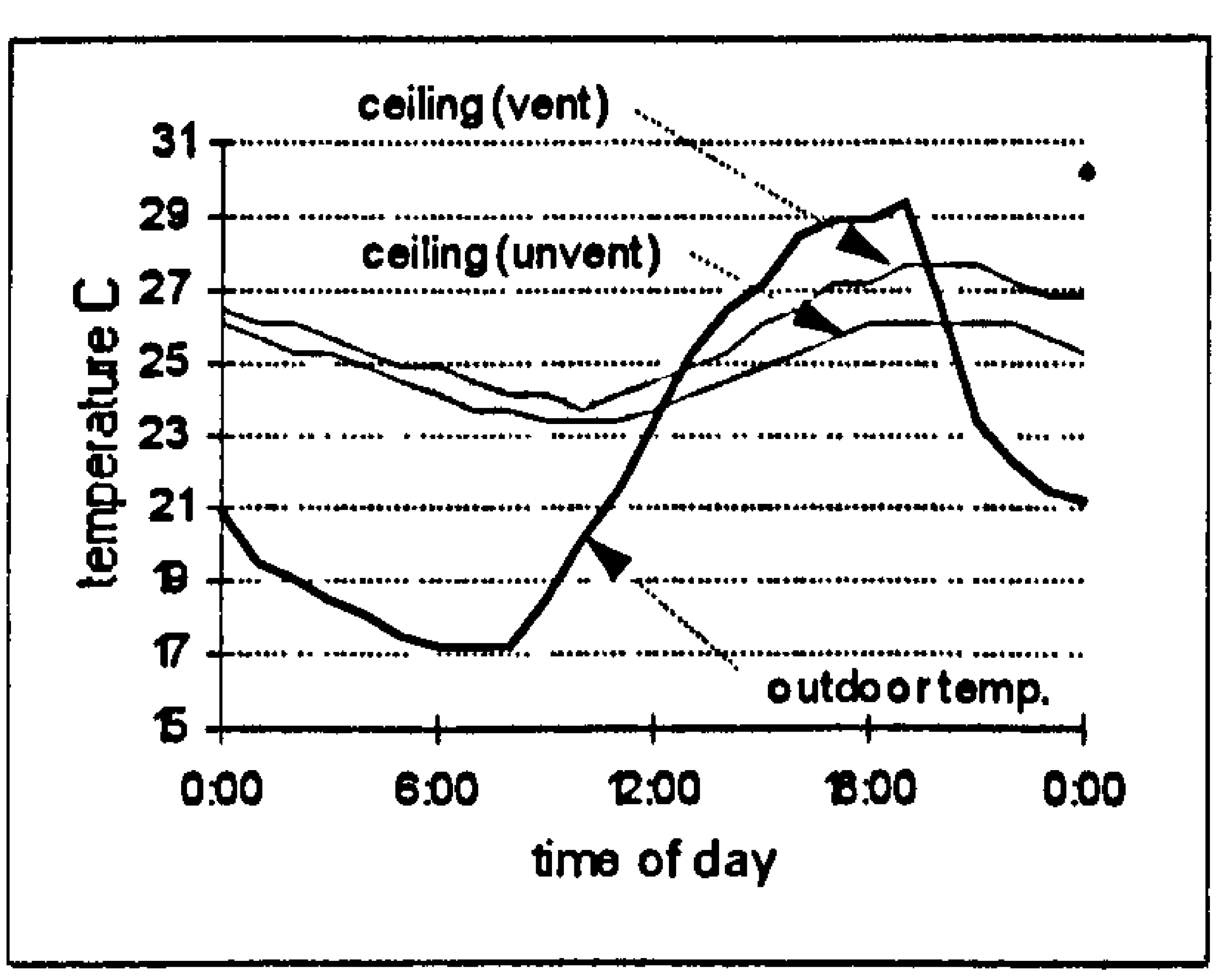
The thermal exchanges between the external air and the surfaces of the internal spaces of the building can be observed from graphs in 5.20. The charts show the temperatures of the external air and the internal surfaces both , under the effect of night ventilation and when the windows were closed. This can help to visualise the effect of night ventilation on the temperature of the building mass.



a) internal wall surface



b) partition surface



c) ceiling surface

5.20 Effect of ventilation on the temperature of internal surfaces

A general observation which applies to all three surfaces considered is that it appears that ventilation of the room was not making the surfaces become cooler. In fact, the surfaces of the wall, the ceiling and the partition began to cool down at night the days after the building was left unventilated but also unoccupied. This seems to point out that the effect of internal gains was being greater than the effect of convective cooling. As mentioned in the section on ventilation, the ventilation rate in this building was maintained relatively low considering the high openable window area and the favourable wind speed and direction. This resulted in higher average internal temperatures than it could have been obtained with further ventilation. Because the windows are totally controlled by occupants, it is assumed from these experiment that 24 °C, the average temperature during the occupied period, was within the comfort range for the users.

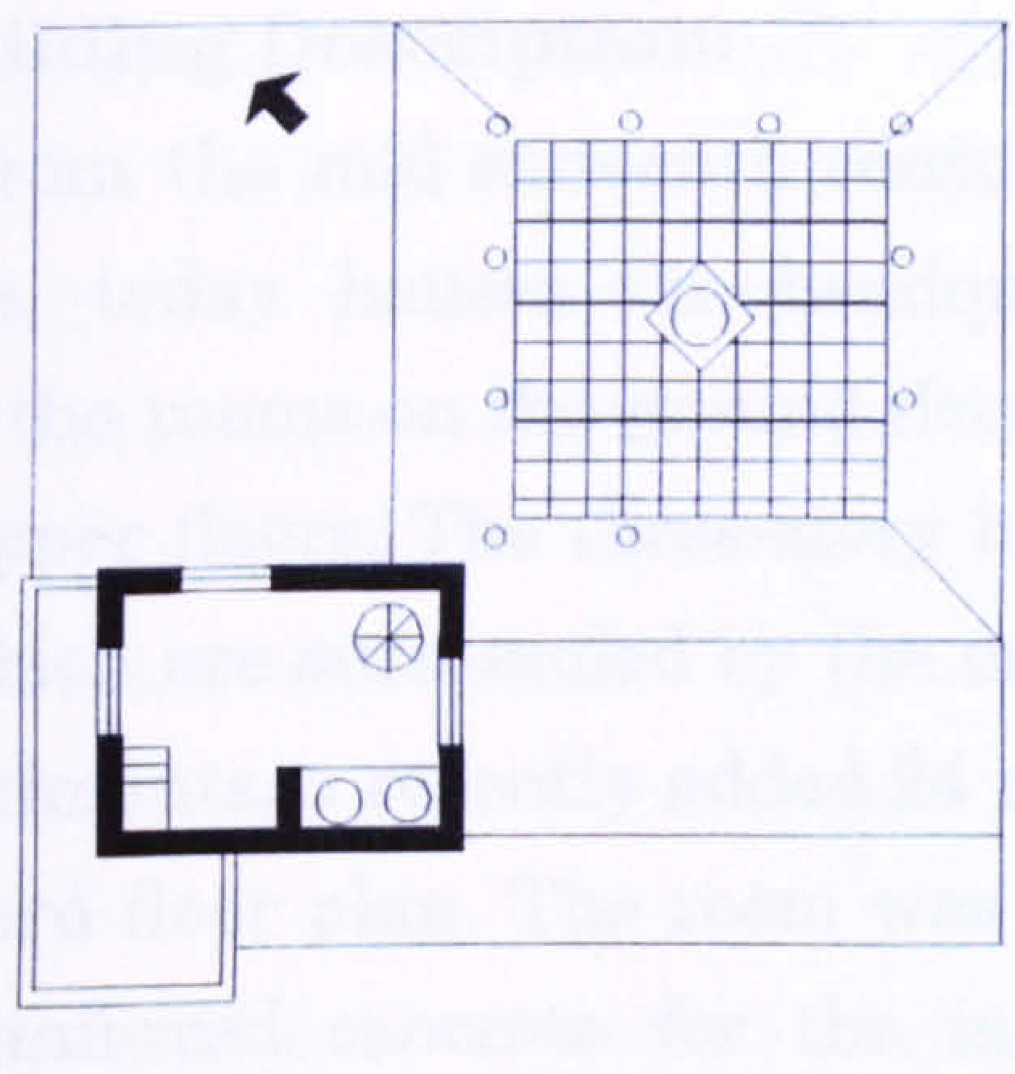
It is suggested that when the building was occupied, the internal surfaces absorbed an amount of heat from the internal air which the incoming cool night air was unable to dissipate. The airflow rate obtained in the building was not sufficient to make the surfaces cooler than they were without ventilation, when the building was not occupied. Chart 5.20 indicates that the internal wall surface increases as a result of ventilation when the external temperature rises to 29 °C and that this process is not reversed at night when the outside air becomes cooler. However, when the building was unventilated, the temperature difference between the internal surface of the wall and the external temperature decreased during the night hours.

5.4 Case 3: *TOWER*

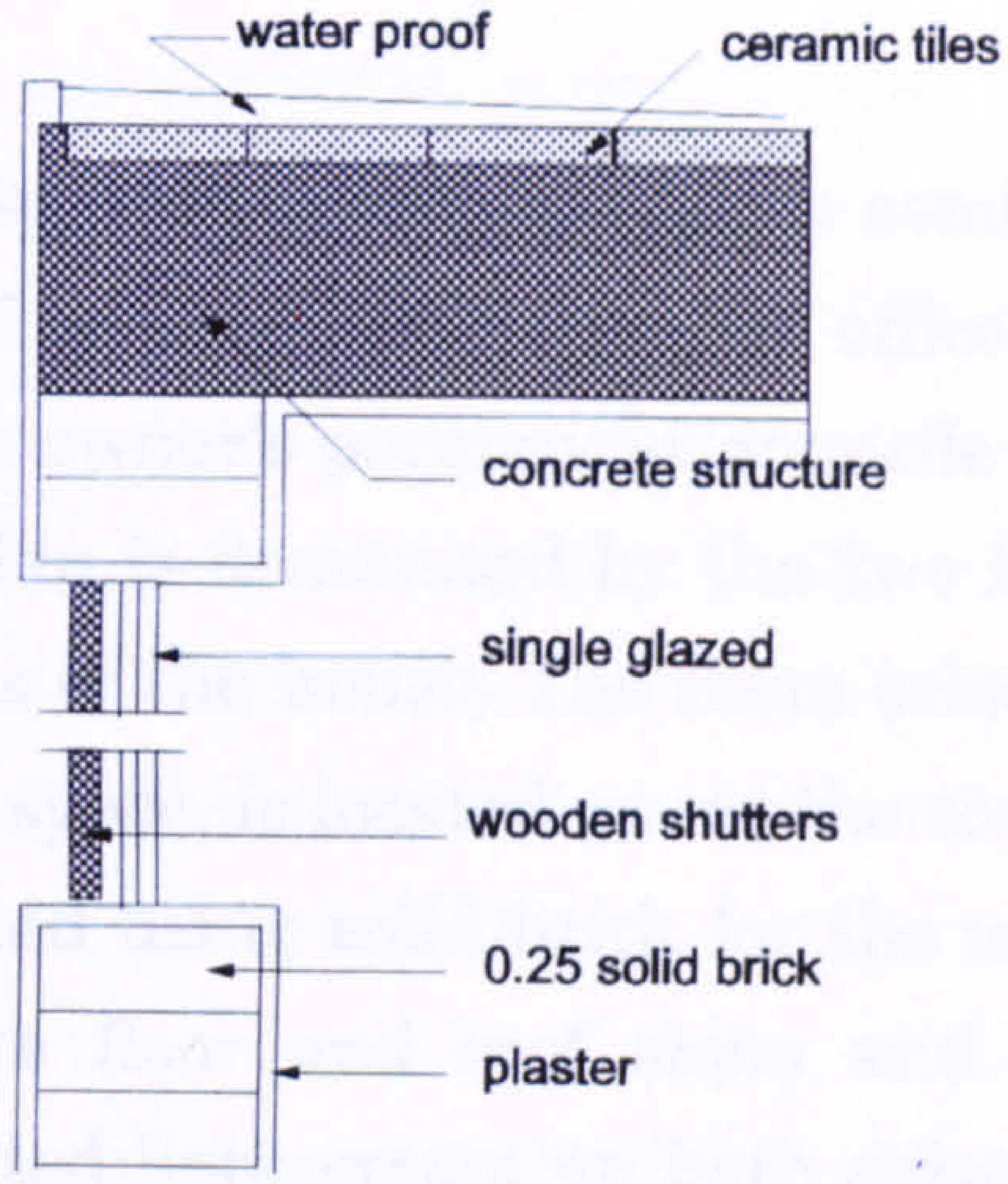
The city of Seville lies on the 37° north latitude and 6° west longitude in the west part of Andalucia, Spain. This historic urban centre, well known for its traditional massive court-yard buildings, provided the setting for the third example of this field work.

5.4.1 Site Location and Climate

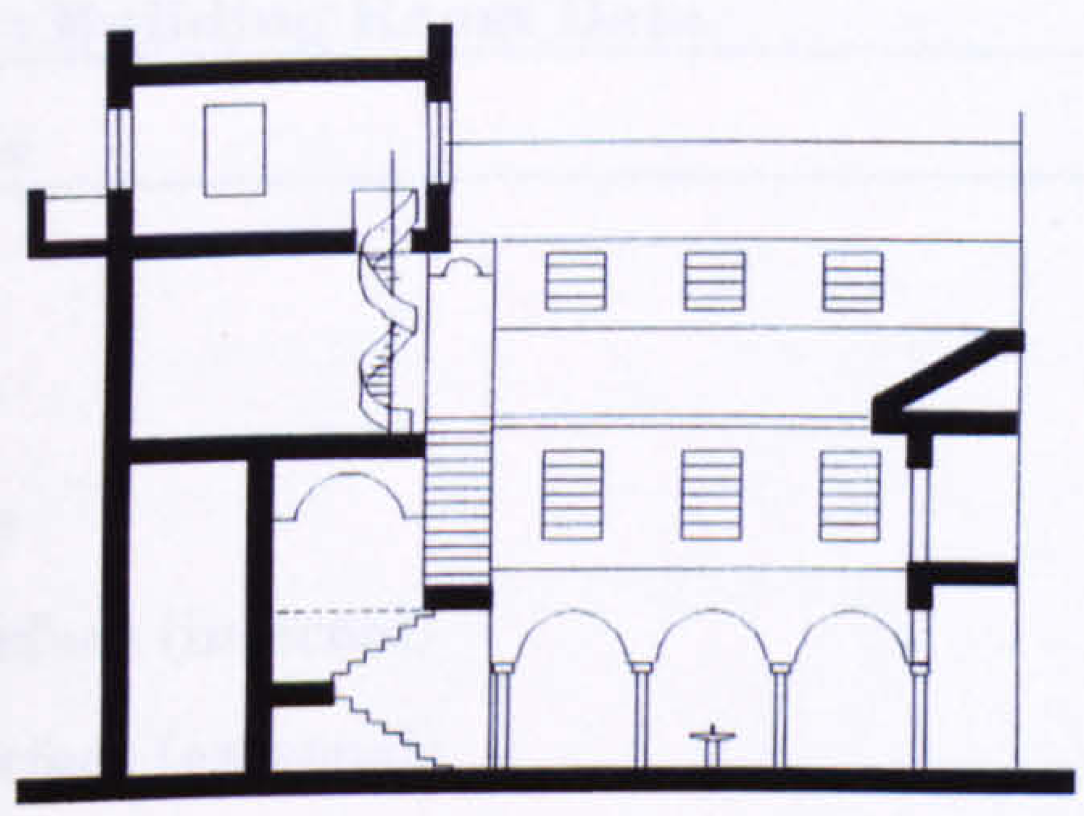
The site is located on the west part of the old town a few blocks form the Giralda, the city's Cathedral. Its high density surroundings which constitute a major feature of the urban configuration of the area, are mainly made of three-story court-yard buildings, small plazas, narrow streets, and tight walkways and pavements. The climate of this region is classified as Mediterranean temperate. The annual mean temperatures fluctuate between 15 °C - 10.3 °C - 6 °C in winter and 36 °C - 28 °C - 20 °C in the summer. However, due to a large diurnal temperature swing in this location, temperatures over 40 °C are frequent during the hot period. Winds are predominantly west and south-west and relative humidity ranges between 25% to 60% in the summer and up to 70% in winter.



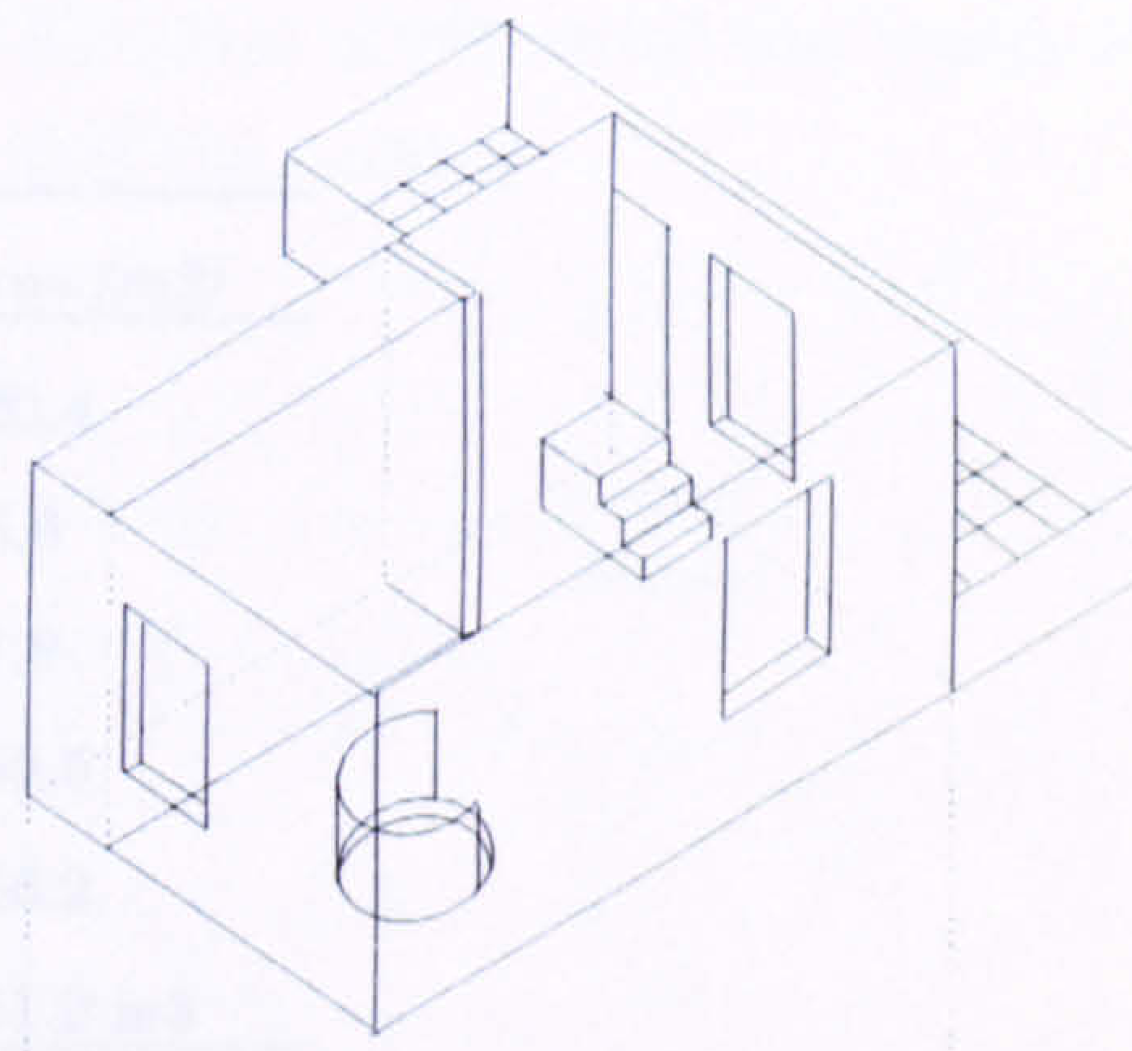
Plan



Wall Section



Section



Axonometric

south facade

central patio

5.21 Building 3: *Tower*

5.4.2 Building Description:

Dating from the mid sixteenth century, this terraced building, once a semi-palace residence, today houses the headquarters of a local architectural office which occupies the rooms on the ground floor, and the owner's permanent domicile located on the upper floors. The three-story building plan is dominated by the two internal patios which are surrounded by the main rooms of the house. The room selected for the experiments, a recently added 24 m^2 studio space, is located on at the south end of the third floor plan. The room was constructed using solid brick for the masonry walls, reinforced concrete for the intermediate floor and roof slabs and all the internal surfaces are plaster finished and painted light cream on both sides. Table 3.1 summarises the room data.

Table 5.5 : Building Room Data

Elements	*Area (m2)*
floor	*20.4
glazing	5.6
openable	7.8
mass surface (internal)	60.5
mass surface (external)	56.2
room volume	61.2 m3

* This value is the effective area of the room.

5.4.3 Environmental Features

The room has a fairly square shaped plan and because it raises above the upper level of the building, all four walls and the roof, are exposed to the exterior. The three windows are located on the north-east, the north-west and the south-east facades and the opaque facade is oriented south-west therefore, it is exposed to the sun most of the day.

Table 5.6: Ratio of Envelope to Floor Area

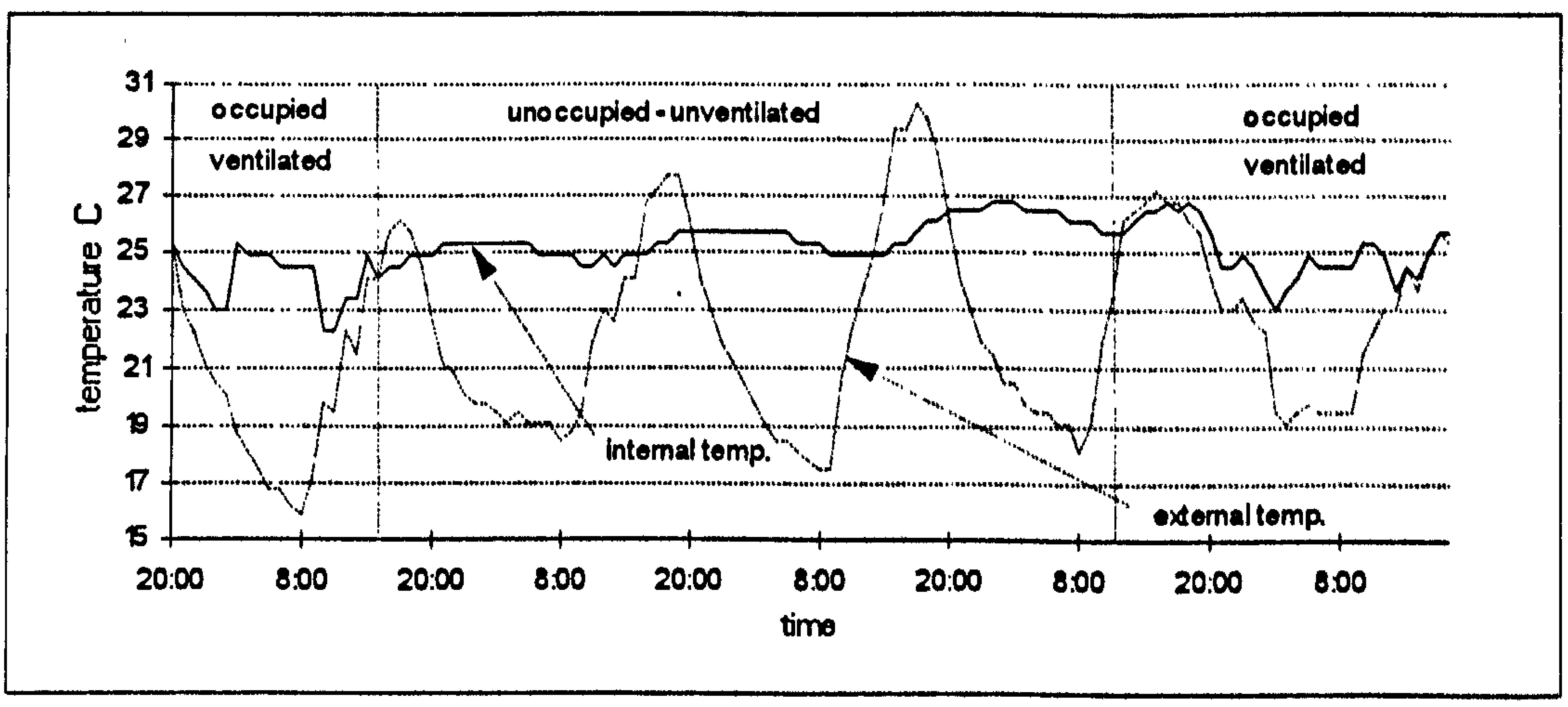
Elements	*Ratio*
glazing / floor	0.27
Opening / floor	0.38
mass surface / floor (internal)	2.96
mass surface / floor (external)	2.75

The values above were calculated for the room of experiments only.

The windows are not externally shaded but are provided with internal wooden shutters for this purpose assisted by roll blinds which also help to control daylighting. The building skin is uninsulated and concentrates the bulk of the room's thermal mass on the 0.40 m thick roof slab. The containers for the hot water supply of the house are located in a small compartment on the south-west wall enclosed with wooden doors. These are thought to contribute to the internal gains of the room although no measurements were made in this respect.

5.4.4 Thermal Monitoring Experiments

The experiments were carried out in this studio space for a period of six days in mid September. The data loggers collected the following data: external and internal air temperatures, temperatures of the external and internal surfaces of the south-west facing wall and the surfaces of internal partition and the ceiling.



5.22 External and internal temperatures with ventilation and occupancy schedules

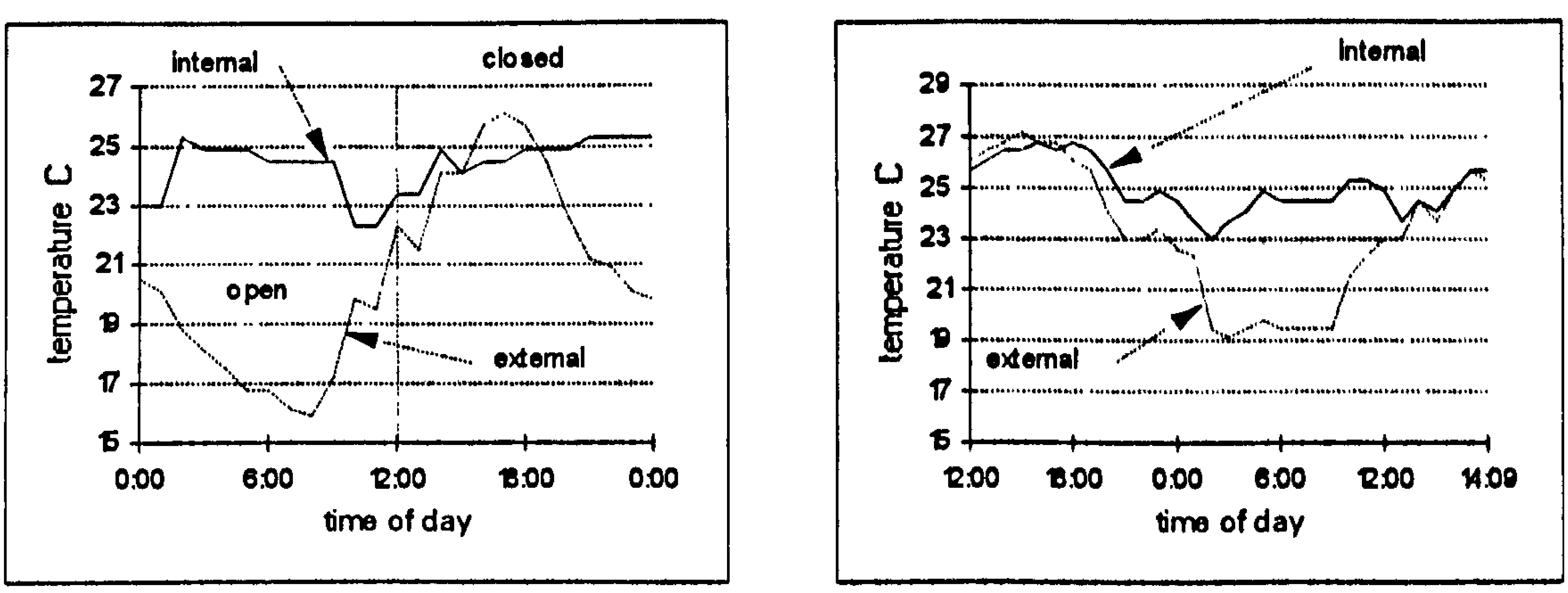
The external temperature recorded appears to agree with the local weather data for that period which was uncharacteristically mild. It maintains, except for one day, a fairly constant swing throughout the monitoring interval with an average temperature of 23 °C. The internal temperature curve shows a fairly constant amplitude throughout the mid part of the six-day period; the temperature oscillation shown at the ends of the graph represents the effect of both, the occupancy and ventilation. The south-west facing wall of the room, which provided the larger exposed opaque mass area of the room to the external environment, was selected for the measurements of external surfaces. No major obstructions existed for the experimental room at this time of the year so that the solar incidence on this wall was effective from about 10:00 AM until around 6:30 PM, shortly before the sunset.

5.4.5 Effect of Ventilation

The effect of ventilation on the internal temperature is indicated by the first and last days of the monitoring period when the building was also occupied, 5.22. During the remaining three days, the room was kept unoccupied and unventilated for the purpose of thermal mass analysis. When the wind blows at 0.5 m/sec and the outside air is 7 K cooler than the inside's, which is the case at night, the ventilation rate of this room can reach over 60 ACH, (from BREEZE simulations). This value is relatively high due to the large window area to volume ratio of the room. Moreover, as the wind speed increases during the day, the air change rate can easily be duplicated if all windows are left open until the consequent decrease of the temperature difference forces it down gradually.

5.4.5.1 Night Ventilation.

The effect of opening windows at night while keeping them shut during the day is shown in 5.23-a. Under the effect of internal gains, the small volume of this room make the effect of night ventilation look unable to cool the internal air for the best part of the night.

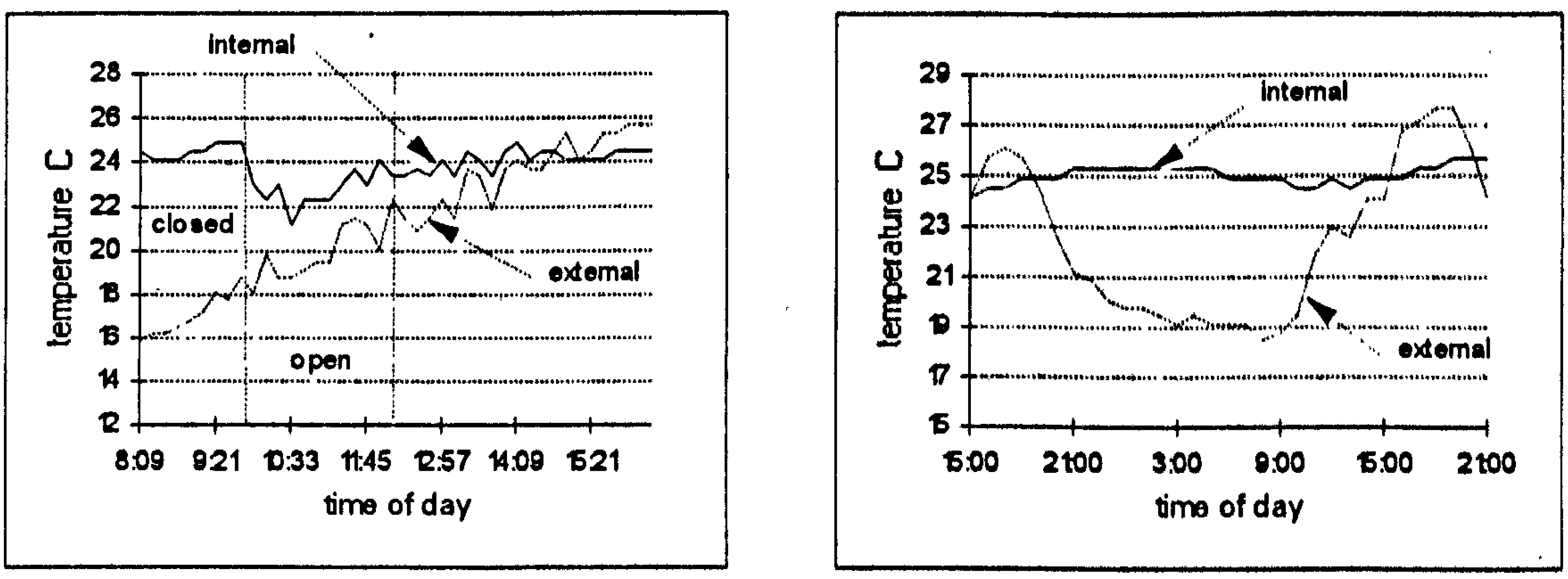


a) night ventilation *b) continuous ventilation*

5.23 Effect of continuous and night-time ventilation

The high night ventilation rate obtainable in this room seemed yet inadequate when the room is subject to internal gains, especially during the first night when ventilation was provided (see graph 5.23). Although the conditions of the room were noticeable altered around midnight, possibly a reduction of window aperture or/and increment of internal gains, the tendency of convective cooling is evident during the first 6 hours of the evening and again soon after 8:00 AM when the outside temperature is still well below the inside's. The effect of ventilation during these hours of the morning is shown separately in graph 5.24-a . Note how the internal temperature line begins to follow the external as a result of an increase of the ventilation rate.

The cooling effect of nocturnal ventilation for the room is also clearly shown during the last day of the experiments when windows were left open all night and during a good part of the day after.. The elevation of the internal temperature due to internal gains during night-time is less accentuated in this case. The quick response of ventilation in this room due to the high ACH rate is also noticeable by the variation of temperature observed soon after the windows were open.



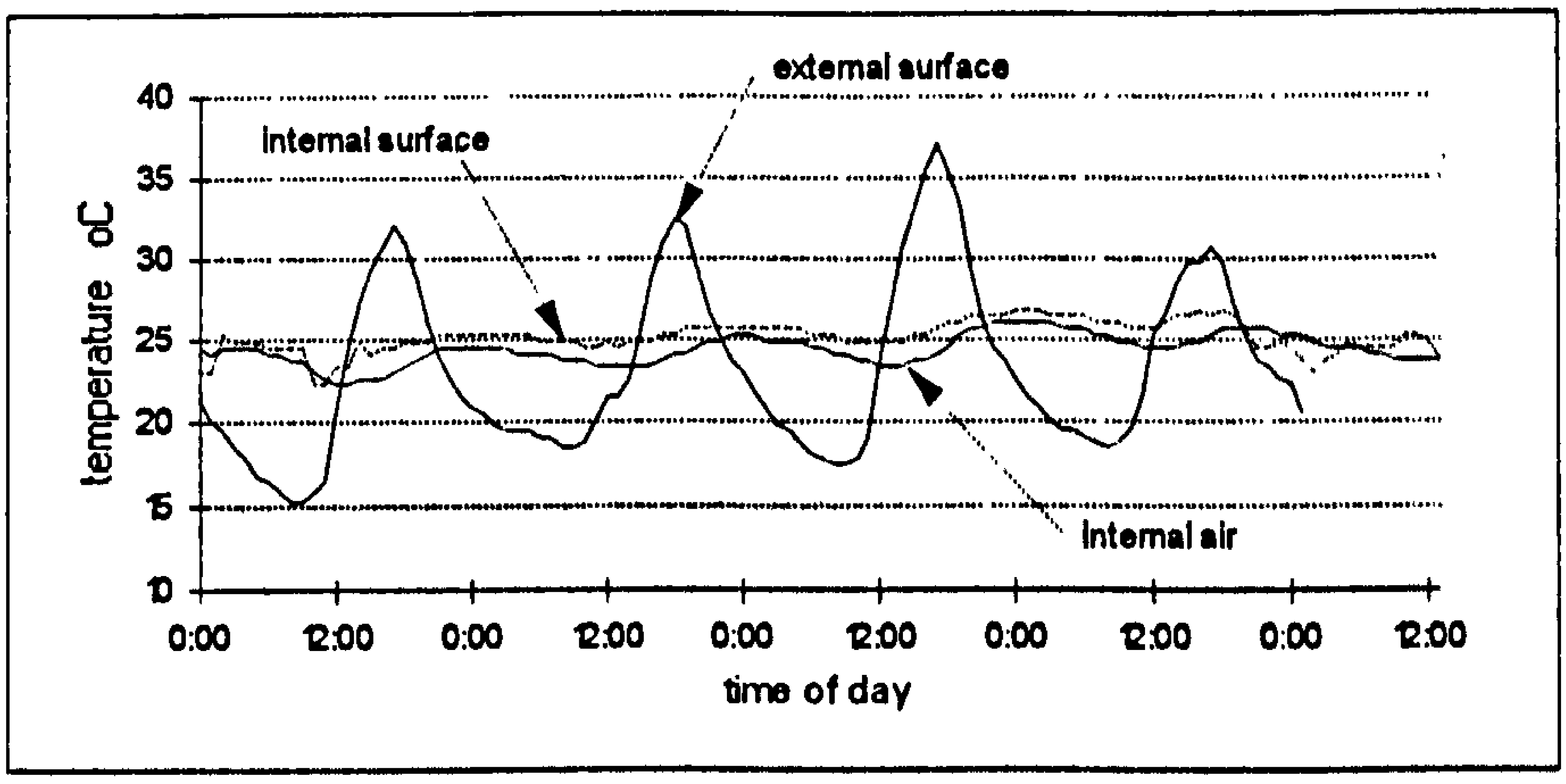
a) opening and closing windows *b) unventilated*

5.24 Effect of ventilation on the internal temperature for different window apertures.

Graph 5.24-b shows the small diurnal variation of temperature when the building was unventilated indicating a good room air tightness and also helps to highlight the strong influence that ventilation can have over the internal temperature. No major alterations on the internal temperature were recorded during these days until windows are finally open in the last evening of the experimental period.

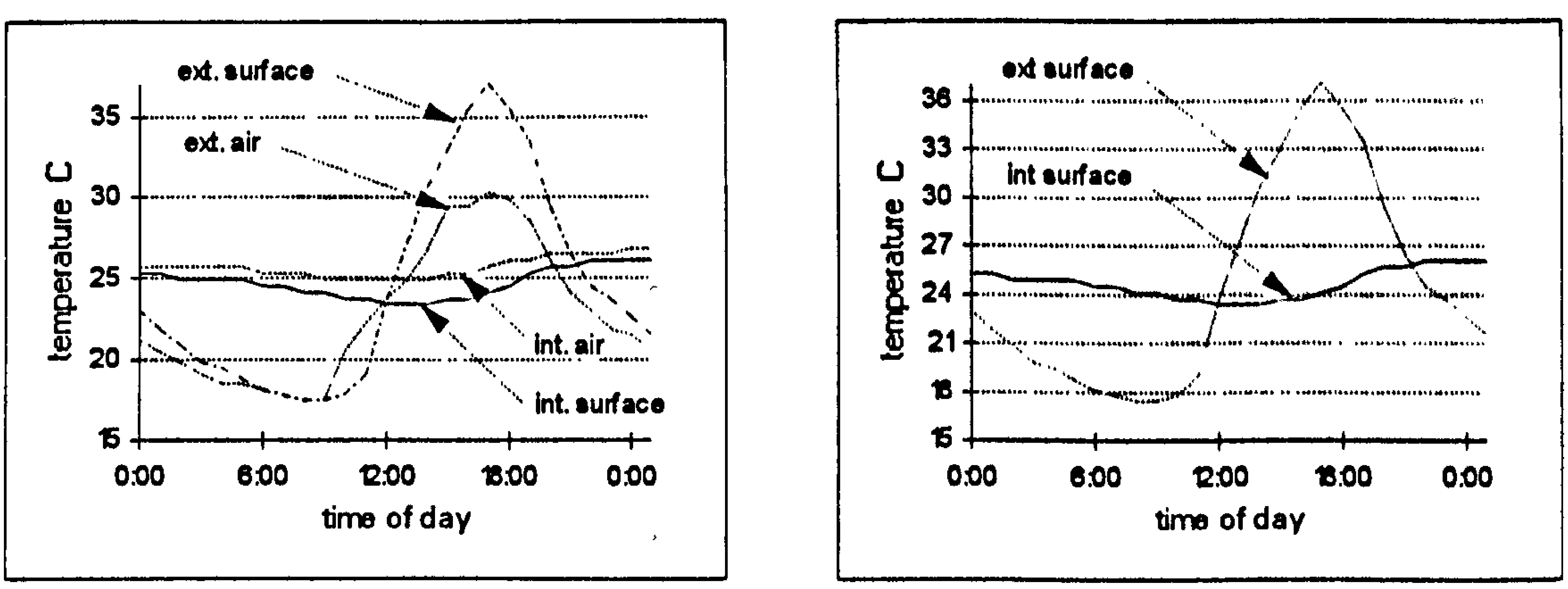
5.4.6 Effect of Thermal Mass

The 0.30 m thick masonry wall used for the measurements of external and internal wall surface temperatures, together with the ceiling and partition surfaces, provided the data for studying the influence of the room's thermal mass on the internal environment. The external wall, constructed with 0.12 x 0.24 x 0.06 m solid clay bricks with a 30 mm plaster finish on both sides (see wall section in 5.21), has no insulation and is oriented to the south-west. Graph 5.25 shows the external and internal surface temperatures of the envelope wall for the 6-day period of measurements. The external surface temperature curve showed a direct correspondence with the external air temperature providing clear evidence of the hotter and sunnier day which elevated the surface temperature of this wall to 37.5°C.



5.25 External and internal wall surfaces and internal air temperature for various days.

The significant effect of the thermal capacity of this wall is clearly shown by the temperature difference created between both surfaces (up to 13 K when the external surface reached 37 °C).



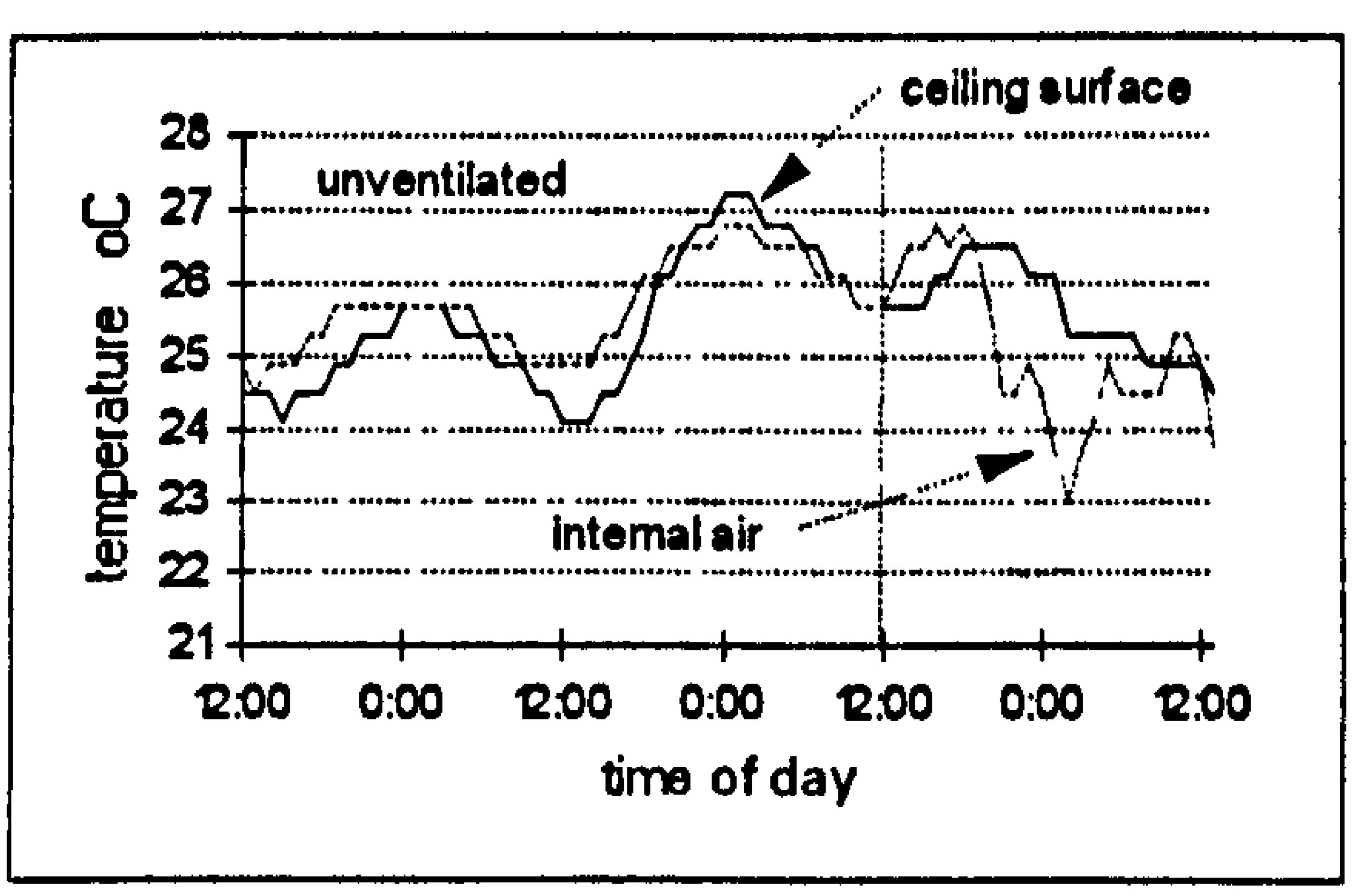
a) air and wall temperatures *b) wall surfaces*

5.26 Temperature characteristics of the envelope wall

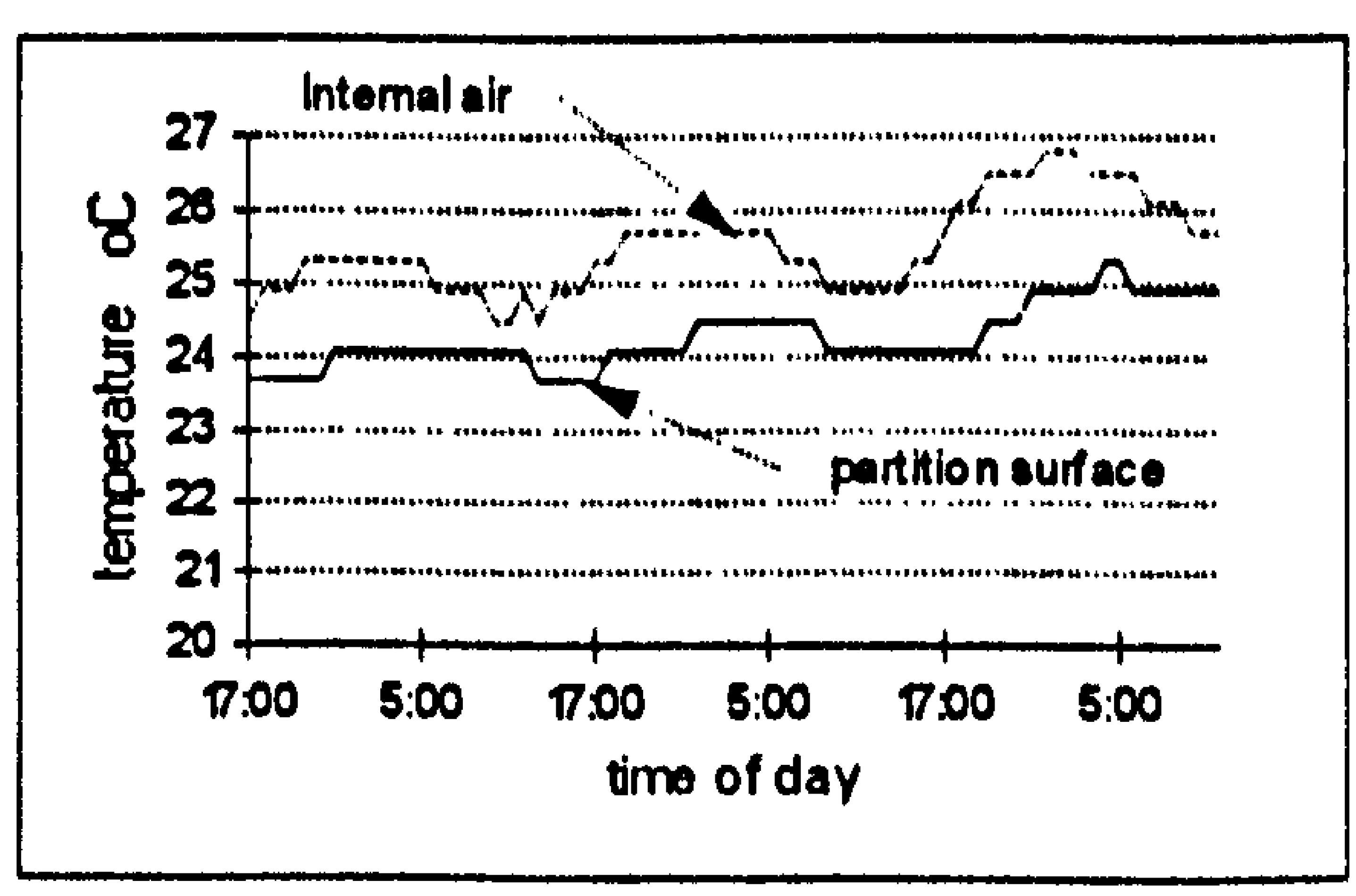
Despite that the wall is not insulated and that the materials of the wall are relatively conductive, the internal surface did not appear to have been affected by the temperature of the external surface of the wall. The temperatures of the outside air, the external wall surface, the internal wall surface and internal air are shown simultaneously to illustrate the temperature flow to and from the inside of the rooms through the envelope wall when the building is not ventilated, 5.26-a. The curves indicate a maximum temperature difference of 7 K between the outside and inside air of the room occurring during the early hours of the morning. During the afternoon as the outdoor temperature rises and the temperature of the room remains virtually unaffected due to the thermal inertia of the structure, the temperature difference decreases to 5 K, the inside cooler than the outside, indicating that the mean internal temperature during the day stays around 1 K above the external temperature. The 12 hour time lag created by the building mass can also be observed in 5.26-b.

5.4.6.1 Temperature of Internal Surfaces

The sensor for the internal surface of the envelope wall was placed at 1.20 m. from the floor. The internal surface of this wall is not oriented towards a window therefore, its temperature was not directly affected by incoming ventilation air. The temperature of the inner surface of the external wall maintained a fairly constant difference of around 1 K above the internal air temperature during the unventilated cycle, 5.27.



a) ceiling surface temperature



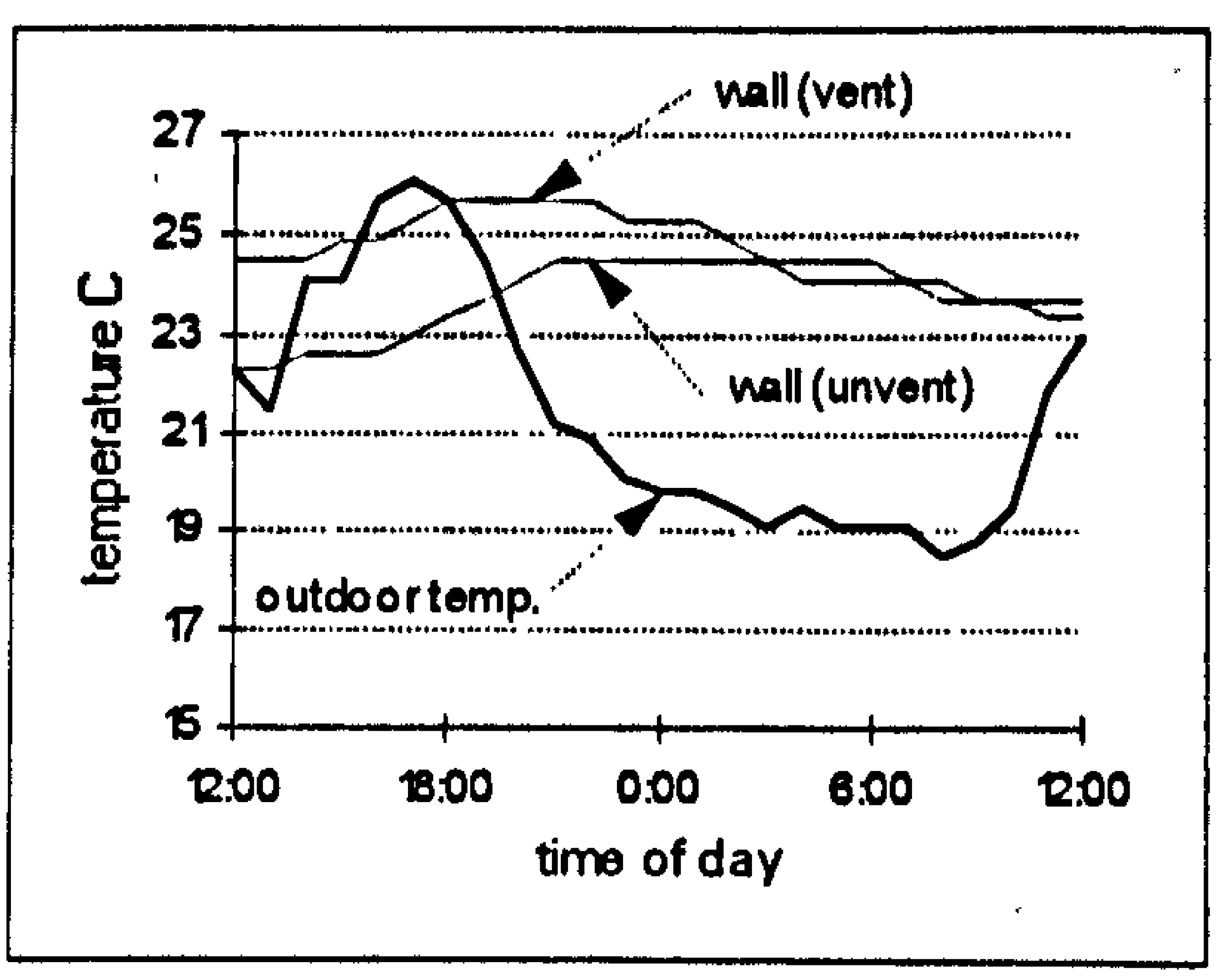
b) partition surface temperature

5.27 Temperature characteristics of the internal surfaces

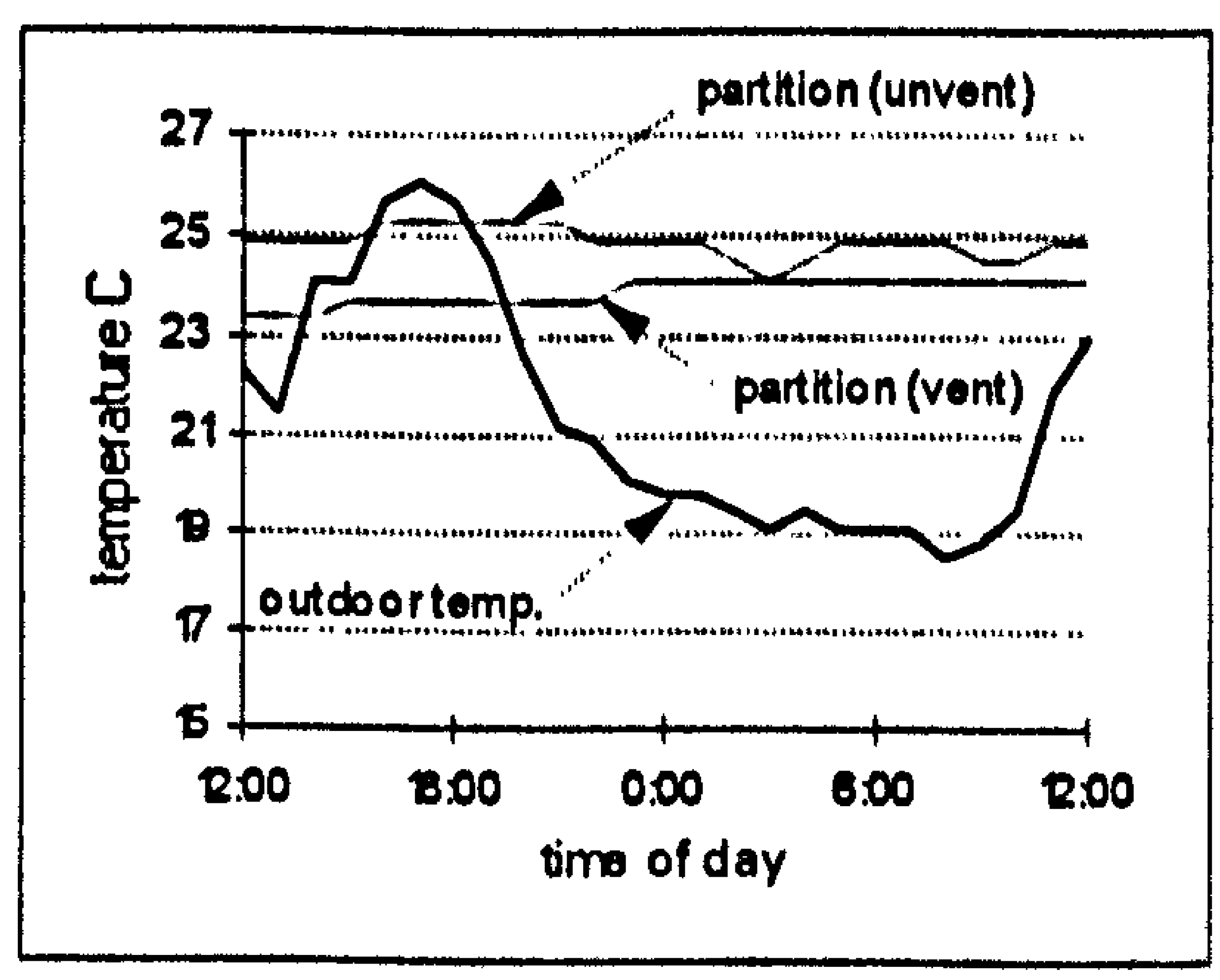
However, the curves indicate that under the effect of night ventilation, the wall's internal surface looses heat at a greater rate dropping its temperature below that of the internal air. Graph 5.27-a relates the temperatures of the inner surface of the ceiling with the internal air temperature. Unlike the internal wall surface, the ceiling surface temperature fluctuates around the air temperature during the unventilated cycle becoming warmer during the day and cooler at night. When the room is ventilated, this convective effect is not sufficient to cool down the ceiling surface beyond 23.5 °C when the air temperature comes down to 22 °C. The temperatures observed on the internal surface of the ceiling appear to have been produced mainly by the effect of internal gains and the hot air which tends to rise to ceiling level. The surface of the internal partition appeared once again to be the most insensitive to the thermal variations occurring within the room even during the period when ventilation was provided. During the unventilated period, the partition surface was constantly maintained 1 K - 1.5 K warmer than the air. Although these two temperatures came closer when the room was ventilated the air temperature dropped below the partition surface. Even so, these temperatures never rose beyond 27 °C and the diurnal temperature variation is the smaller in comparison to the other internal surfaces. This partition wall is a small internal massive element of about 1 m^2 of exposed surface area and it has the similar thermal capacity as the external wall.

5.4.6.2 Internal Surfaces and Ventilation Air

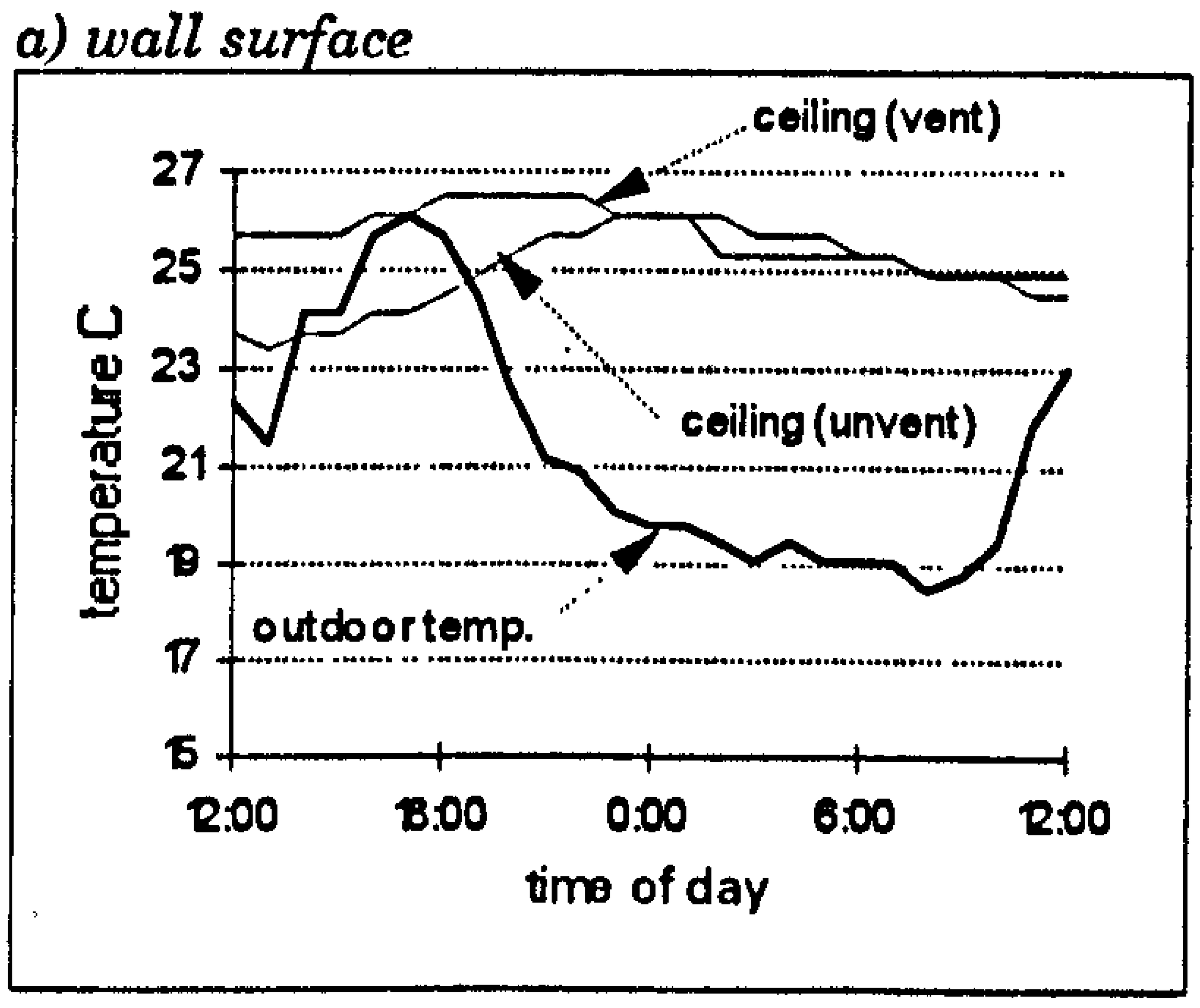
Due to the internal gains by occupants which had a greater effect on the internal temperature in this building, the effect of night air for cooling of the internal surfaces was more noticeable.



a) wall surface



b) partition surface



c) ceiling surface

5.28. Effect of ventilation on the temperature of internal surfaces

Although the temperature of the internal surfaces did not come down as low as the temperature of the external air, there is a tendency for the mass surface to cool down with the night air, especially the surfaces of the wall and the ceiling while the partition is the less affected. The graphs in 5.28 show the temperature of the surfaces when the room was ventilated and when it was unventilated. Although the difference in temperature between the ventilated and the unventilated case is not more than 2 K, the tendency for cooling is well apparent.

Additionally, the cooling effect of night air is illustrated by the fact that the room surfaces became cooler the night when ventilation was provided, even when the external temperature was not as low as the night when the room was unventilated. Once again, the cooling effect of night air was more evident on the wall and ceiling surfaces than on the internal partition. The experiments in this building like those of building 2, Salteras, emphasise that the impact of internal gains can offset the effect of night ventilation if this is not adequately provided.

5.5 Case 4: *CARMONA*

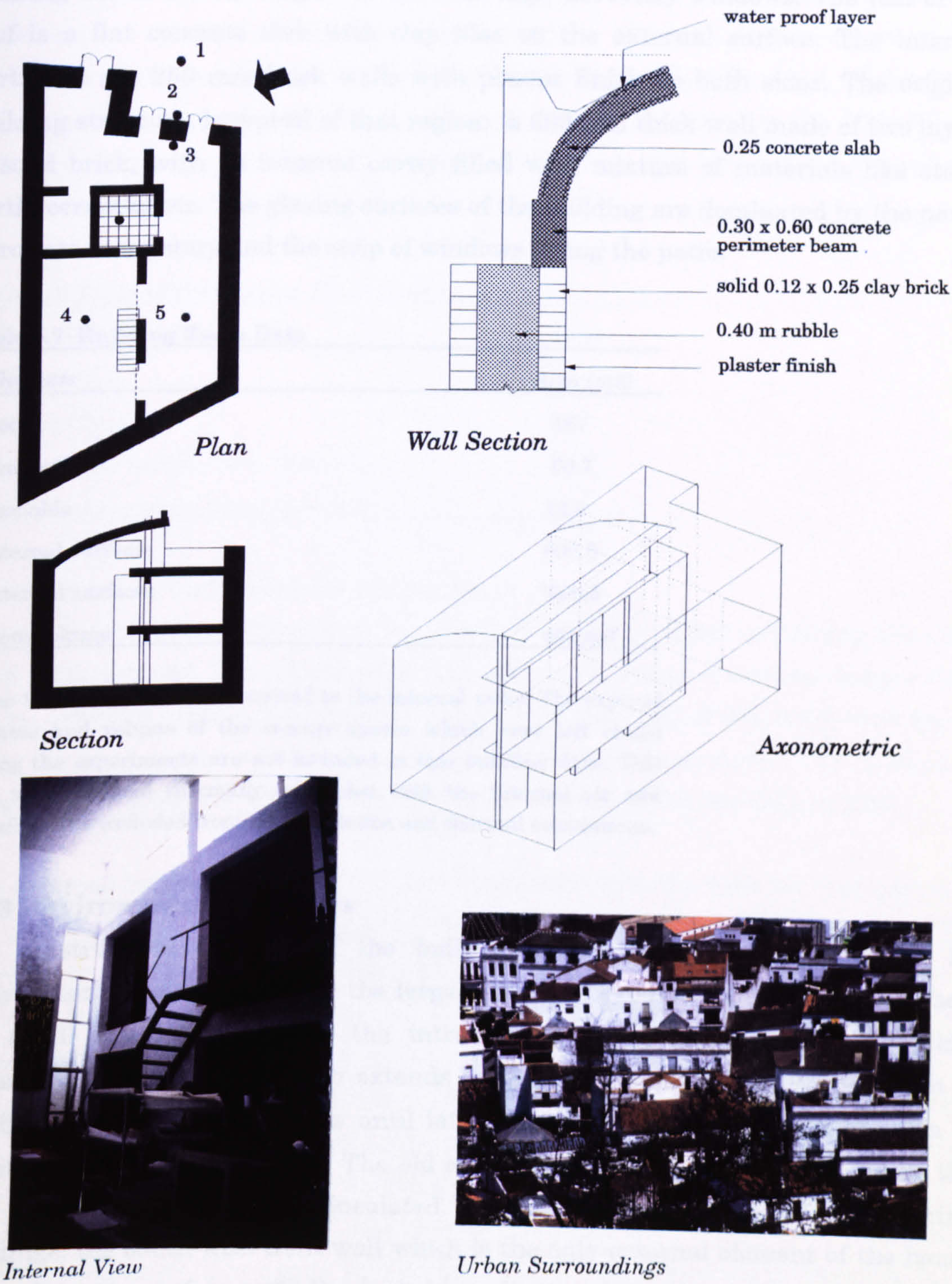
Carmona is an Andalucian seventeenth century town located at 28 km to the north-east of Seville. The fourth example for the experiments was selected from this old urban centre which maintains to date its local constructional traditions.

5.5.1 Site Location and Climate

The site is located on the east part of the city. The town is constructed over an area of irregular topography at an altitude of 248m above sea level. The building surroundings of the site are characteristic of the small villages of the region of Andalucia, mostly two and three-storey white washed roof tiled houses grouped around narrow passages and small plazas. Although it is a low rise city, the place 's tight arrangement enhances its urban density. The higher altitude of this area makes its micro-climate slightly cooler and more humid than that of Seville, particularly because it is exposed to fresher winds coming from the Atlantic reducing its average temperature by 1 K-1.5 K. Additionally, the city's urban grid reduces considerably the amount of solar radiation on the vertical surfaces.

5.5.2 Building Description:

This two-story building is part of the historic part of the town and its original construction date from the late XVIII or early XIX centuries. Although some renovations have been carried out on the interior, the house's external envelope is still the original. The building has a dual use as a one-person residence and an architectural office studio.



5.29 Building 4: *Carmona*

A major transformation made to the building in recent years is the curved roof built over the main working area. This is a reinforced concrete slab with no finish other than white paint on the inside which raises toward the south side of the plan creating the necessary height for the 2 m. high clerestory windows. The rest of the roof is a flat concrete slab with clay tiles on the external surface. The internal partitions are 250 mm brick walls with plaster finish on both sides. The original building structure, is typical of that region: a 600 mm thick wall made of two layers of solid brick, with an internal cavity filled with mixture of materials like stone, earth, ceramics etc. The glazing surfaces of the building are dominated by the newly introduced clerestory and the strip of windows facing the patio.

Table 5.7 Building Room Data

Elements	*Area (m2)*
floor	167
glazing	30.7
openable	13.5
internal surfaces	608.5
external surfaces	*230.3
room volume	431 m3

* One third of this mass is exposed to the internal patio. The exposed surfaces and volume of the storage spaces which were left closed during the experiments are not included in this building data. This area was assumed thermally uncoupled with the internal air and therefore was excluded from the ventilation and thermal calculations.

5.5.3 Environmental Features

The constructional aspects of the building that appear most relevant to its environmental performance are the large amount of exposed thermal mass surface, the small internal patio and the introduction of the south-west facing $16m^2$ clerestory. The curved roof slab extends beyond the clerestory for the provision of shading in the summer months until late September when the sun rays begin to penetrate through the glazing. The old external walls and original roof unlike the new curved roof are both uninsulated. Due to the constriction of neighbouring buildings, the south-west front wall which is the only external element of the house except from the roof, is partially shaded by adjacent obstructions. The patio is semi-covered with a white canvas to protect the upper windows from direct solar incidence. Stack ventilation can be provided using the lower windows from the patio together with the openable glazed panes of the clerestory. The rest of windows, those located on the front external wall, are not glazed and due to their relative small aperture area these are used to ventilate the rooms at the east-end of the building. There are no shading elements on these windows although the thickness of the external walls help hide the vertical surface of the window for most of the time. These apertures are also provided with solid wooden shutters on the interior and further protection is given by roll blinds on the outside. Table 5.8 shows the ratio of envelope's main surface areas to floor area.

Table 5.8 Ratio of Envelope to Floor Area

Elements	*Ratio*
glazing / floor	0.18
opening / floor	0.08
exposed mass surface / floor (internal)	3.64
exposed mass surface / floor (external)	1.37

5.5.4 Thermal Monitoring Experiments

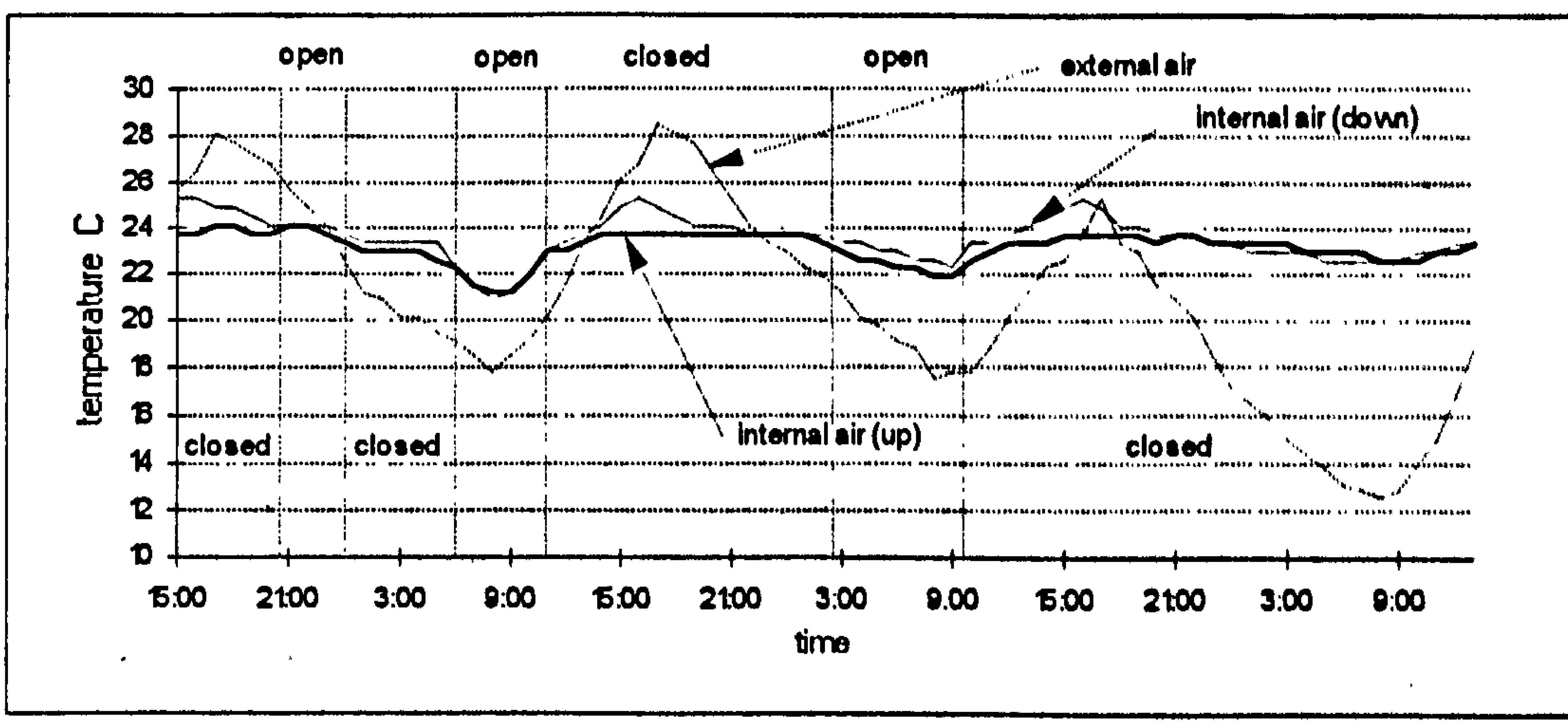
The 4-day monitoring programme for this building was carried out during the third week of September. The experiments included the recording of internal temperature at two different heights, the external and internal surfaces of the south-west facing wall, the temperature of the patio and the external temperature. The location of sensors throughout the building are shown on the plan of the building in 5.29.

The external temperature recorded was uncharacteristically mild for that period of the year although the swing ranged within the average values for this month. The average temperature recorded during monitoring interval is 22 °C. Readings of internal temperature were taken at working plane level on the ground and the upper floors. The average swing of the internal temperature is 2 K. The sensor on the ground floor registered slightly higher temperatures than those of the upper floor because even if no direct radiation is allowed to the interior through the south glazing, the internal wall near to the sensor of the ground floor is more subject to the effect of heat being diffused and reflected from the curved surfaces of the ceiling near the clerestory. The sensor on the upper floor was placed away from the main wall facing the clerestory.

The temperatures taken from the patio indicated that this semi-outdoor space is thermally closer to the internal areas of the house than it is to the outside environment despite that it is only partially covered with the canvas. The average swing is 2 K and the minimum temperature is 2 °C higher than the external.

5.5.5 Effect of Ventilation

The effect of ventilation was monitored during the 4 days of the experiments. Ventilation was provided mainly at night except for the last evening when the outdoor temperature dropped to 12 °C and the windows were maintained closed. The influence of ventilation is clearly shown on the curves during the first two days where the internal temperature lines tend to follow the outside temperature during the window opening hours.



5.30 External and internal temperatures with ventilation schedules

The total capacity of ventilation of this building when all windows are open and wind is blowing at 1 m/sec is around 19 ACH. The ventilation rate supplied during the days of the experiments were determined assuming wind speeds of 1 and 2 m/sec which are typical values for that location at that time of the year. See night ventilation rates in table 5.9.

5.5.5.1 Night Ventilation.

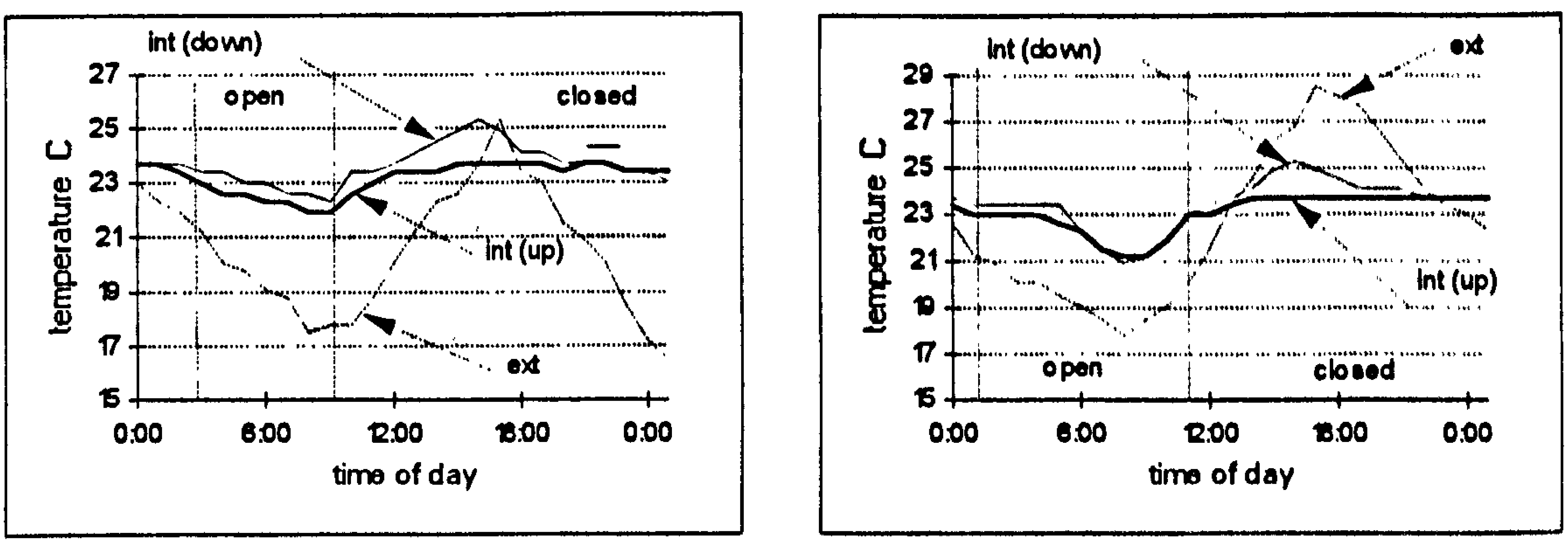
Graphs 5.31-a and 5.31-b show the effect of ventilating the building at night at different rates, according to variations of window aperture as shown in the table 5.9 At 7.9 ACH, the temperature difference observed between the outside and the inside is 5 K. This difference became 3 K when the air change rate increased to 19.2 ACH.

Table 5.9 Night Ventilation Rates and Window Opening Schedule

Night	*Windows G. Floor*	*Windows 1 Floor*	*Windows Clerestory*	*ACH for 1m/sec*	*ACH for 2 m/sec*
1	☐	☒	☒	5.8	11.5
2	☐	☐	☐	19.2	23.6
3	☐	☐	☒	7.9	13.5
4	☒	☒	☒	0	0

☐ Window Open

☒ Window Closed

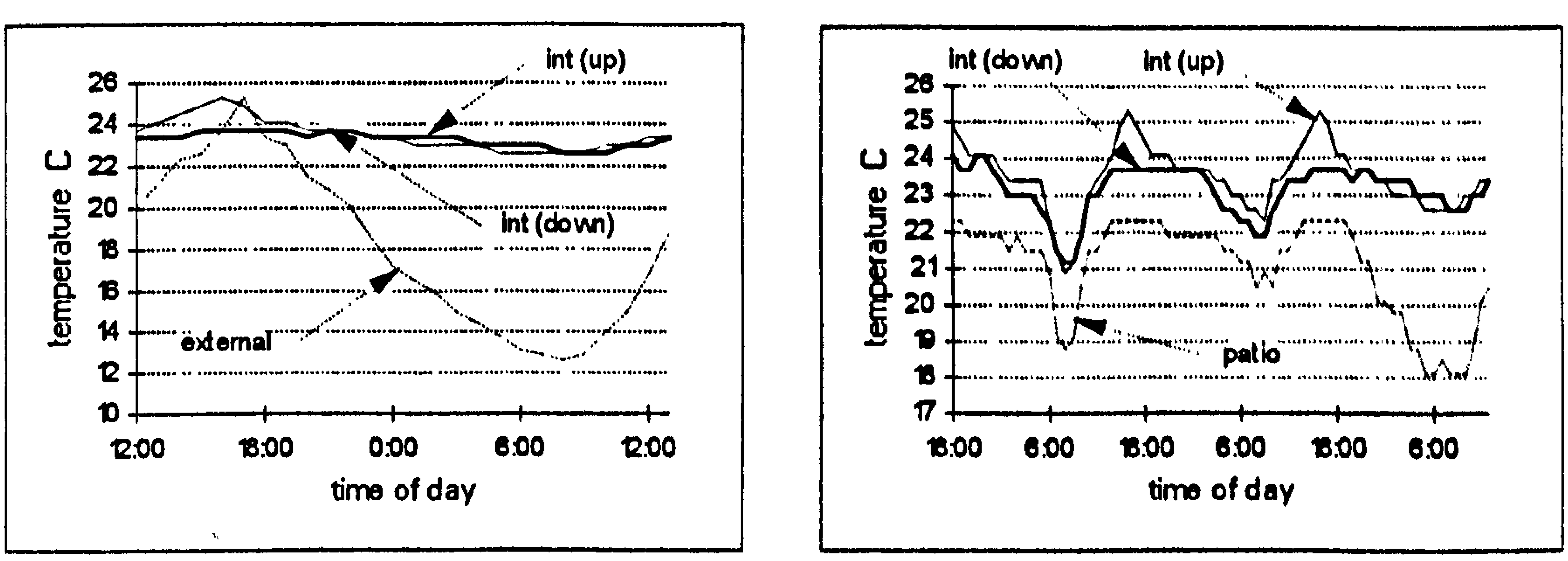


a) 21 of September *b) 22 of September*

5.31 Effect of night ventilation during two consecutive days.

5.5.5.2 Unventilated

When no ventilation is provided, there is little alteration of the temperature line as observed in graph 4.14. The internal temperature is maintained around 23 °C when the outside reaches 13 °C with a temperature difference of 10 C.

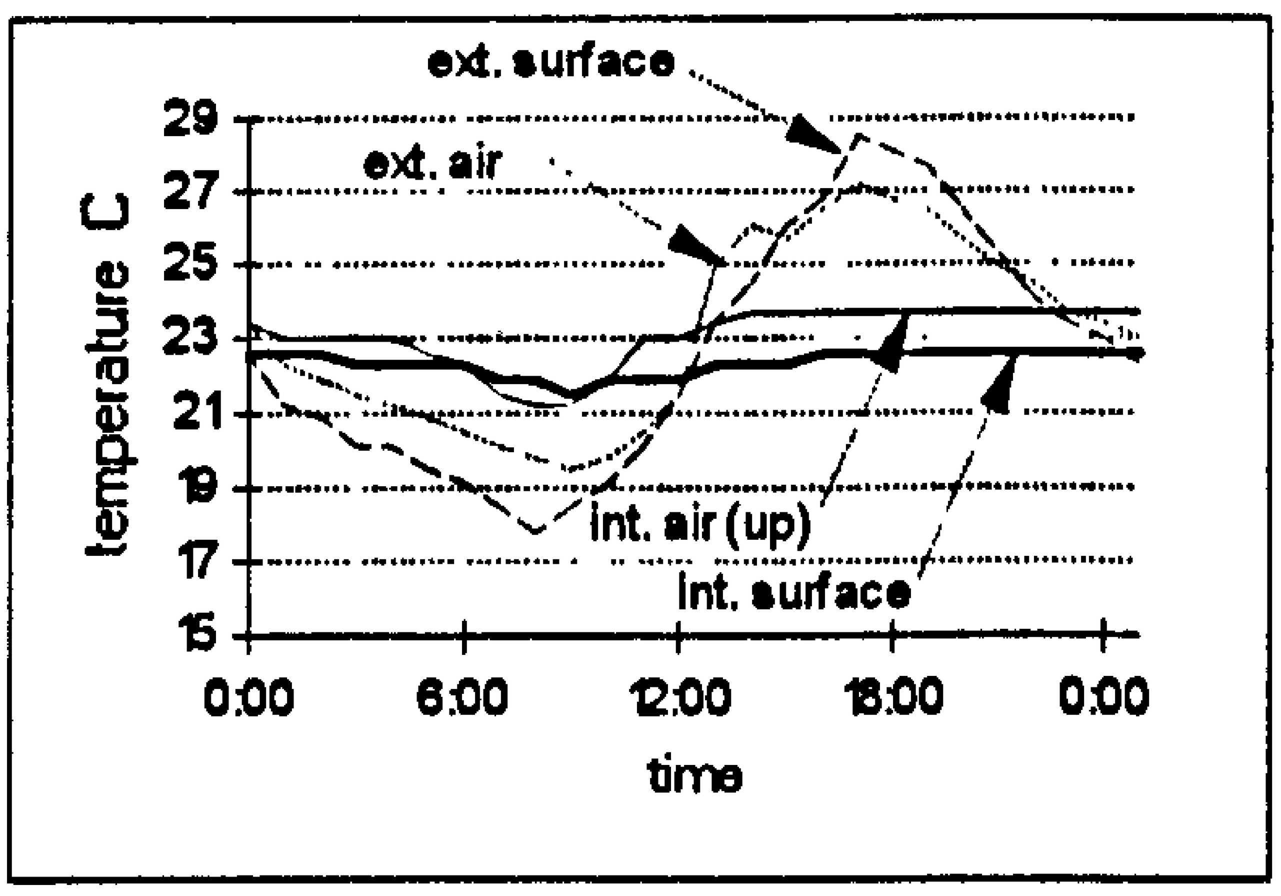


a) unventilated *b)ventilation from patio*

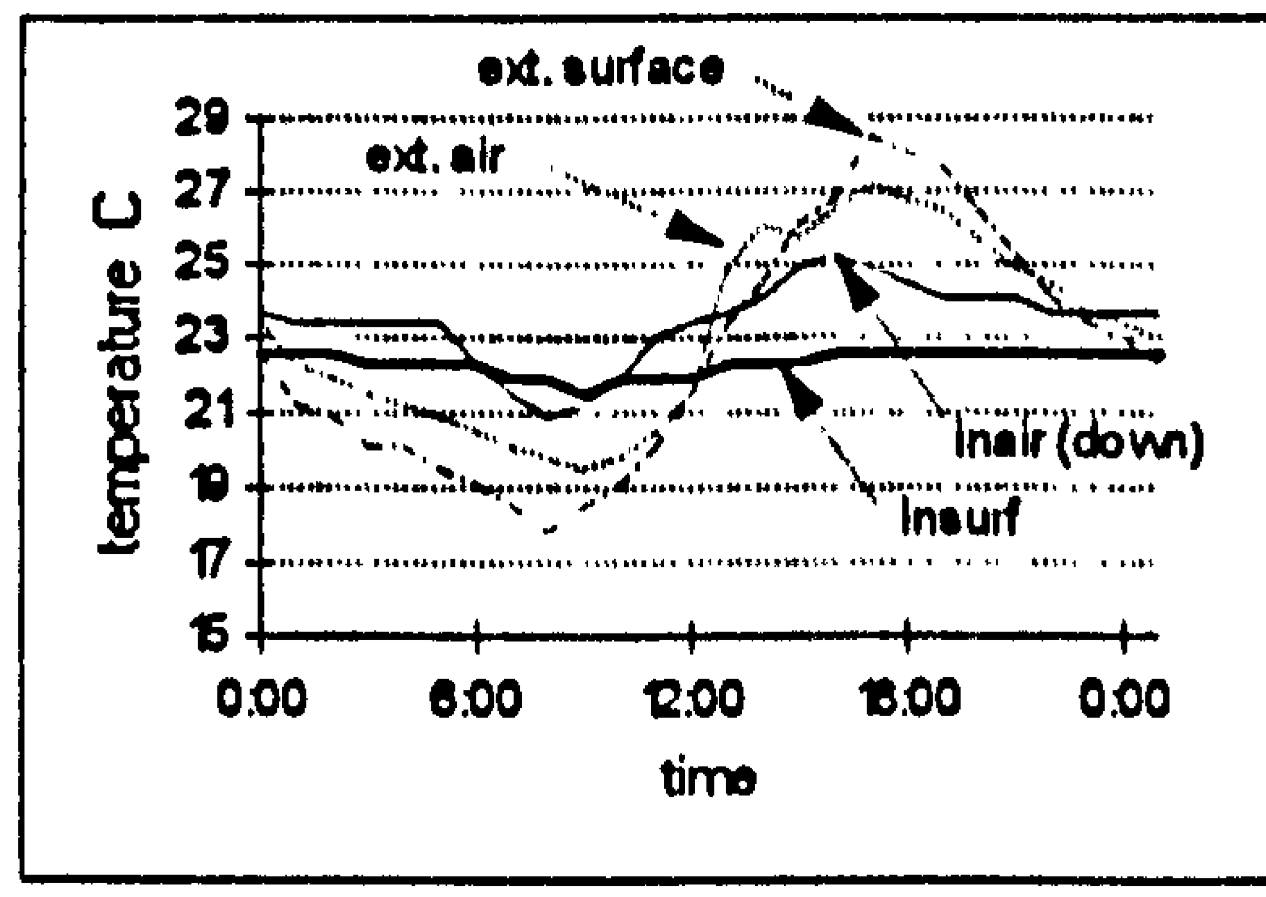
5.32 Internal temperatures for an unventilated day and temperatures from patio

5.5.6 Effect of Thermal Mass

Due to the massive envelope of this building the temperature inside the rooms remain fairly constant during the day. The temperature curves showed a fluctuation of around 3 K when ventilation was provided at night and around 1 K during the unventilated period.



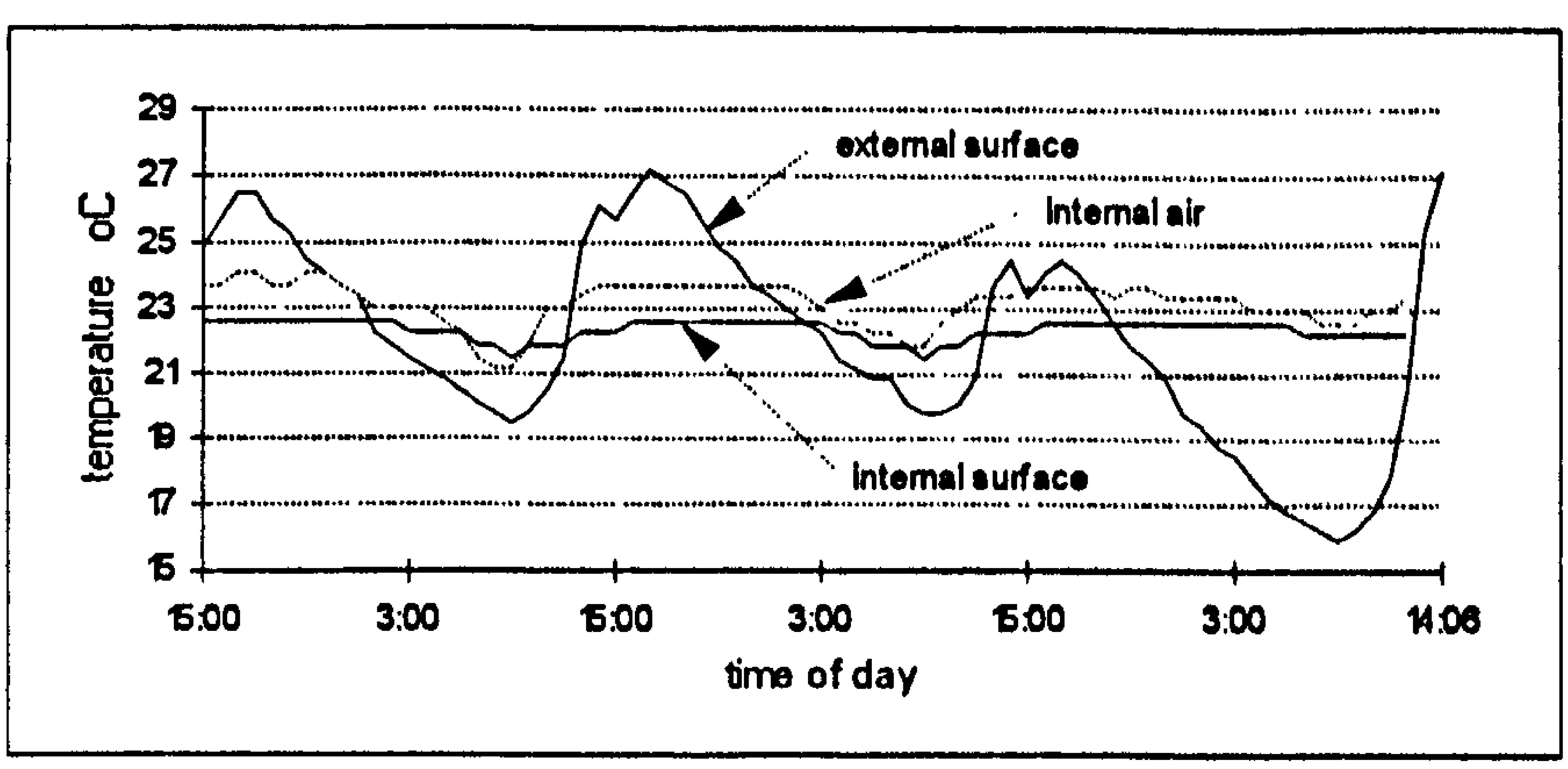
a) air and wall temperatures (mezzanine)



b) air and wall temperatures (ground floor)

5.33 Temperature characteristics of external wall

Temperature measurements of the envelope external and internal surfaces of the front wall help to observe the heat attenuation effect of the building mass on the internal climate despite that this wall is only partially exposed to the direct radiation for about half of the sunshine hours during the day. Graphs 5.33-a and 5.33-b show the temperature flow through the external wall to the ground and upper floors respectively for a 24-hour period.



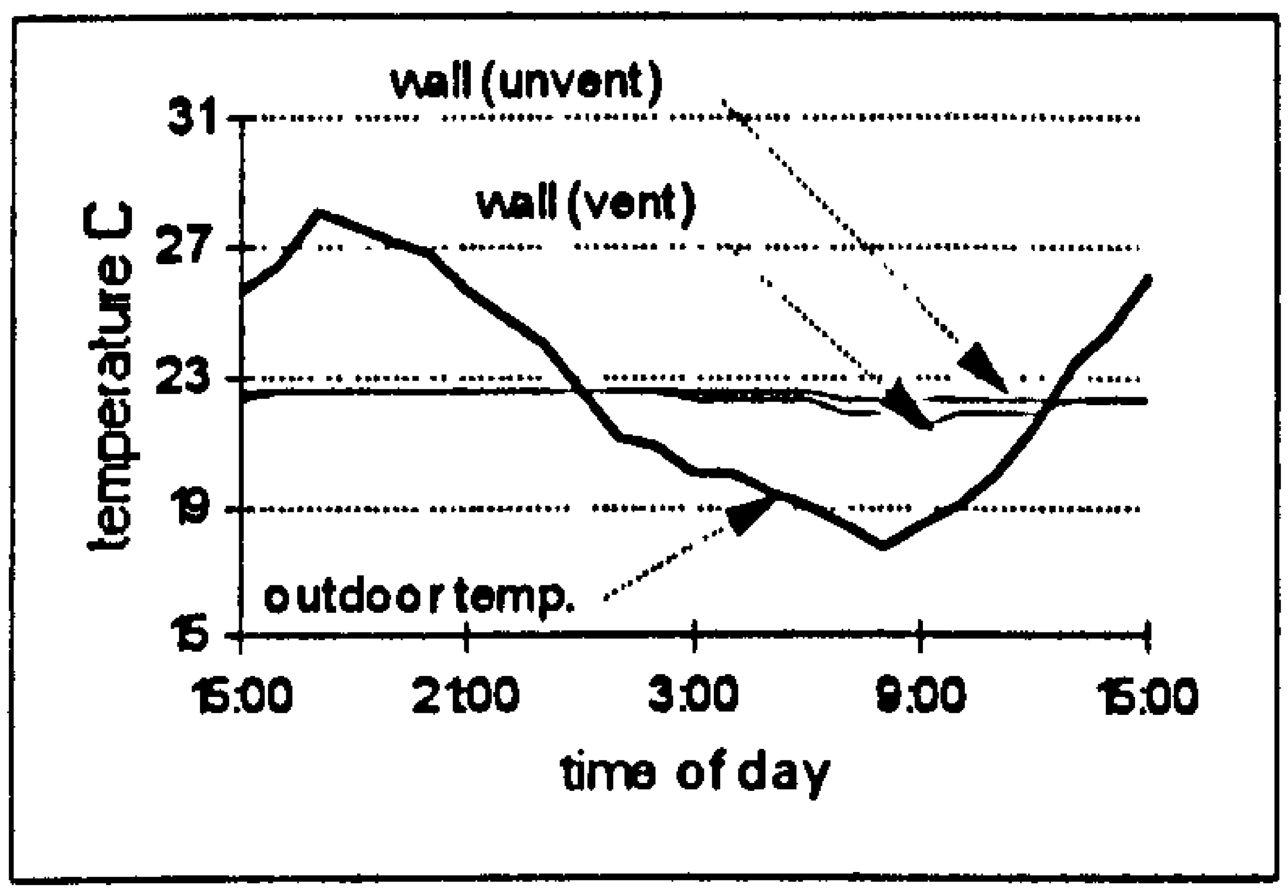
5.34 Wall temperatures at outer and inner surfaces.

5.5.6.1 Temperature of Wall Surfaces

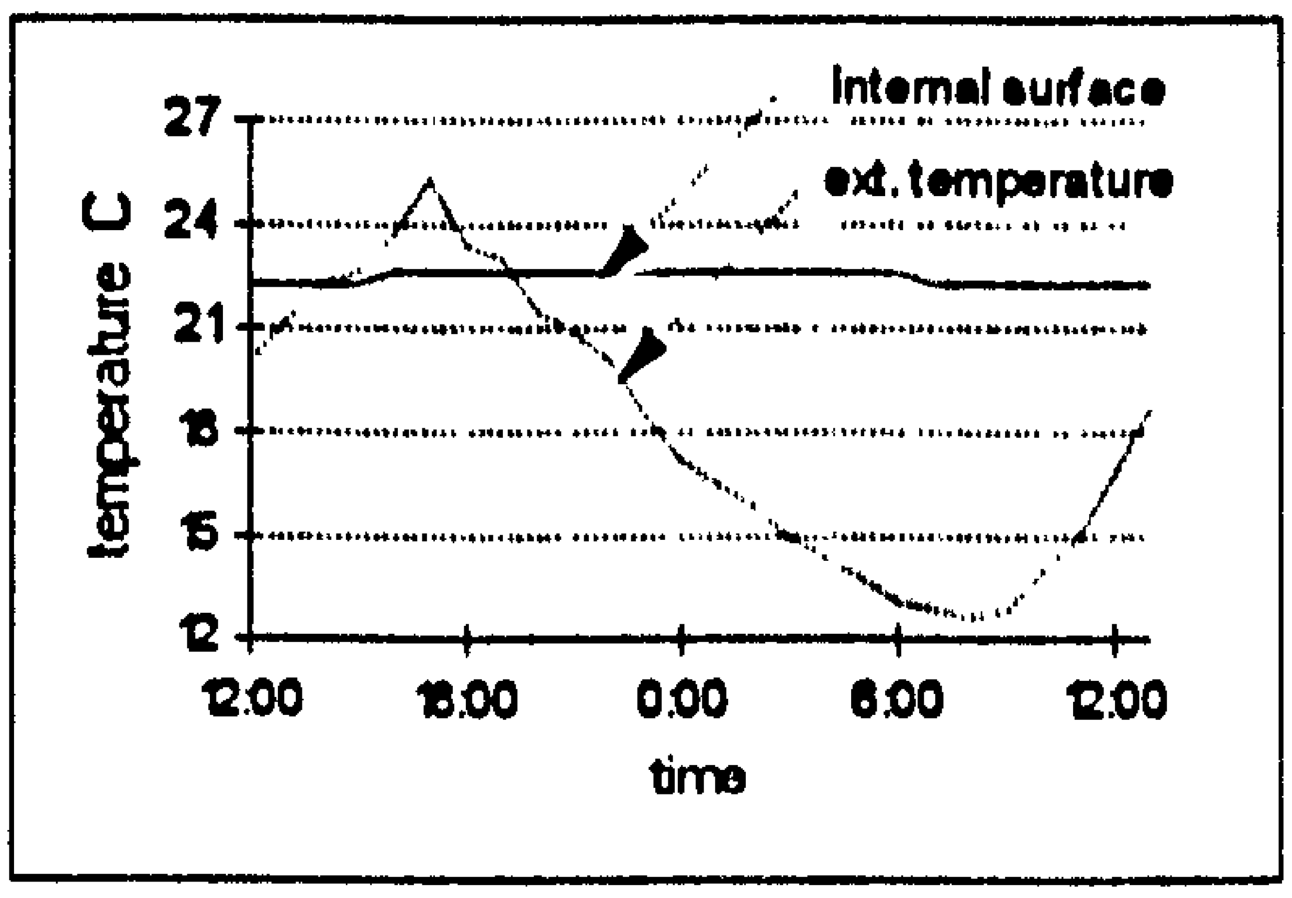
The readings of the external wall surface temperature were taking from the south-east facing wall of the building, the wall surface of the house which have the longer solar exposure. During the overheated period, this wall is exposed to the sun during the morning hours until around 5:00 PM. The temperatures on this surface never surpassed the 28 °C mark. Unlike the previous examples, the temperature swing of the external wall surface is smaller than the external temperature. The internal surface temperature was measured by placing the sensor at 1.00 from the floor on the massive front wall. The readings showed a very small temperature swing (1 K) from an average 22.5 °C mark throughout the experiments. Graph 5.34 shows temperature of the inner and outer wall surfaces for the 4-day period of measurements. The most visible variations on the internal surface temperature are produced by the effect of ventilation at night. Nevertheless, the temperature fluctuation of this surface never went beyond 1 K regardless the variations of the external surface temperature.

5.5.6.2 Internal Surfaces and Ventilation Air

The thermal interaction between the internal surface of the wall and the air temperature both of the inside and outside of the building is shown in graphs 5.35-a and 5.35-b. When the building is cooled at night by ventilation the inner surface of the wall responds becoming almost as cool as the internal air. During the day, when the air temperature rises, the wall surface maintains a lower and more constant temperature.



a) ventilated at night



b) unventilated

5.35 Effect of night ventilation on internal surfaces

5.6 Analysis of Results

The thermal inertia characteristics for each building was analysed within the frame of three global categories: the quantity, the location and the distribution of the thermal mass within the space.

5.6.1 Quantity of Thermal Mass

The quantity of thermal mass was measured by the heat storage capacity of the building as a whole and by its building components individually. The parameter used to quantify the heat storage in the building is the *thermal capacitance*, the product of the density, the specific heat, the thickness and the surface area of the building elements.

5.6.2 Location of Thermal Mass

The mass location criterion allowed the study of the independent effect of the different positions of the thermal mass within the building. This category classifies two groups: the external position and internal position of thermal mass. The external position of mass includes all elements of the building in direct contact with the external environment such as external walls and roofs. The internal position account for building elements with no direct contact with the exterior, i. e. internal partitions, internal floors inter-zone walls, columns, stairs, etc. Within the location of thermal mass category, two groups of variants were considered, the distribution of the thermal mass within the building or zone and the orientation of the external elements.

5.6.3 Distribution of Mass - Mass to Floor Ratio

The effect of thermal mass in buildings varies according to extent of the exposure of its internal surfaces to the internal air. The mass to floor ratio *MFR*, used for the measure of this variable can be expressed as the ratio of the total area of internal surfaces to floor area. The surfaces accounted for will be in direct or indirect thermal contact with the air node of the zone of interest. The direct coupling category refers to the case of walls, floors or ceilings with convective and radiative heat exchanges between them and the thermal node of the zone, whereas the indirect coupling includes the surfaces coupled by the convective portion of heat transfer alone. Surfaces of rooms with permanent closed doors were assumed to be thermally uncoupled and were not included in the *MFR* value. The *MFR* also excluded the portions of surfaces which are covered such as built-in wardrobes, bookshelves and carpeted floors.

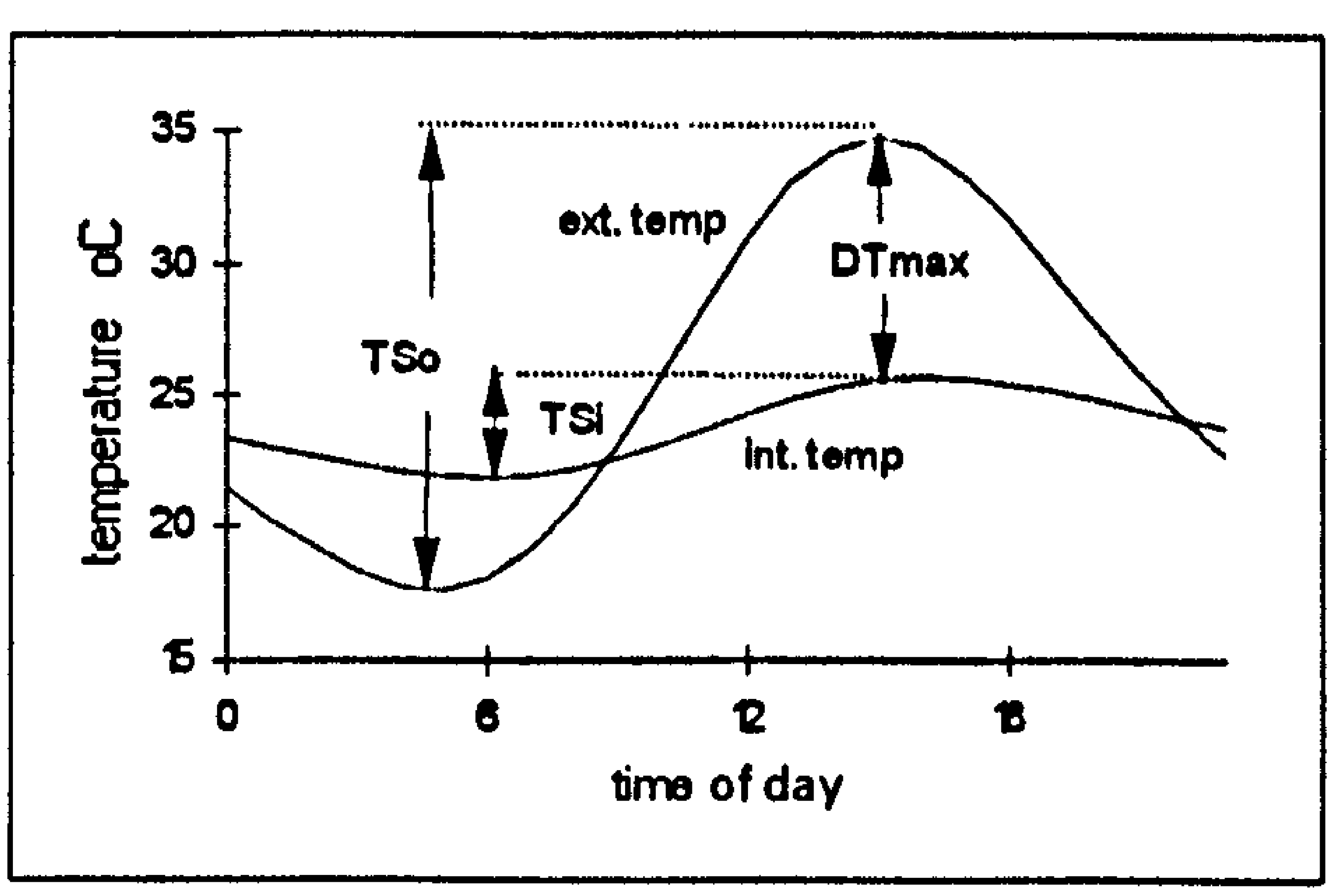
The *MFR* to floor ratio of a room or building can vary according to its geometry, the transparent to opaque surface ratio, and the wall height. For example the reference zone used for the simulation analysis has a floor area of 64 m^2, see chapter 6. If the envelope walls of this room are 3 meters high, the *MFR is* 3.5. If the envelope walls are 8 meters high the ratio will be 6. The *MFR* values which applies to the scale of most buildings range between 3 and 6. This range corresponds rooms with walls between 2 and 6 meters height (see table 6.2). Higher ratios are less common in residential and small office buildings although they are frequent in commercial complexes, exhibition halls, churches, auditoria and other large volume buildings.

5.6.4 Analytical Indices

The Temperature Swing Ratio and the Peak Temperature Difference are the two parameters used in this study to determine the thermal response of the buildings in relation to the external temperature. The *TSR* and the *DTmax* enabled the observation of the thermal effect of a building's thermal mass of without the need for using direct resultant temperatures which may have been misleading considering the variations of outdoor conditions of each individual location.

5.6.4.1 The Temperature Swing Ratio

The *TSR* is the quotient of the external and the internal temperature swings produced in a period of 24 hours. A major effect of the thermal mass of a building is to modify the internal temperature swing. The *TSR* is an indicator of the extent of this modification as a function of the external temperature diurnal variation. A *TSR* value of 1 would indicate that the effect of the building mass on the temperature swing is zero and that both temperatures would be the same.



5.36 Temperature Swing Ratio and the Peak Temperature Difference

Despite that the *TSR* makes no direct reference to the absolute temperature inside the zone, it may help to associate the thermal characteristics of the building with thermal comfort. Thermal comfort inside buildings decreases with large temperature swings. 5.36 illustrates graphically the temperature swing ratio (*TSR*) and the peak temperature difference (*DTmax*) for a typical massive zone. These two parameters were used to study the influence of the building thermal mass on the internal temperature.

TSR = TSo / TSi
DTmax = To (max) - Ti (max)

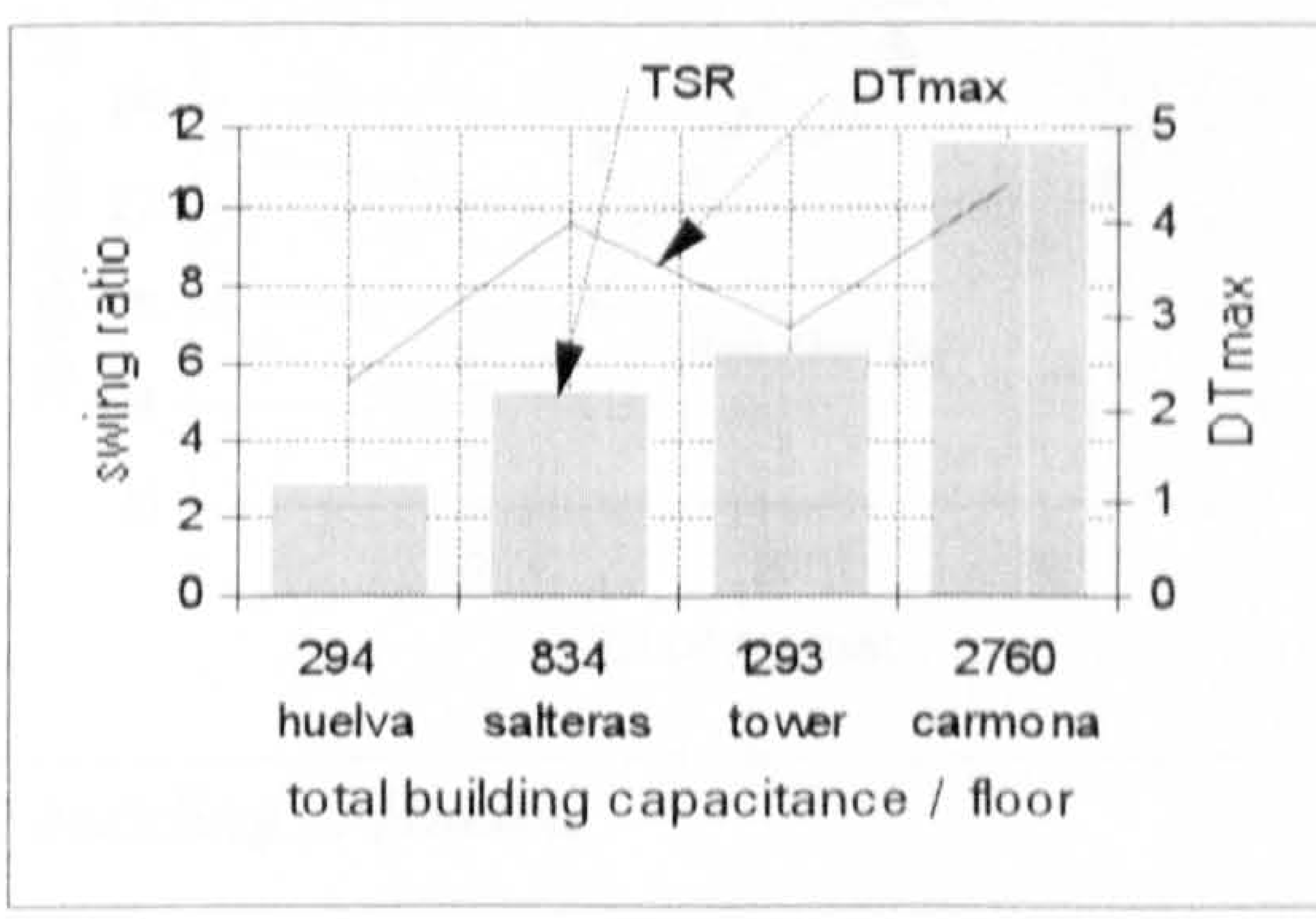
5.6.4.2 The Peak Temperature Difference - *DTmax*

The peak temperature difference is the difference between the maximum outdoor temperature and the maximum internal temperature. This parameter directly indicates the ability of the building to attenuate the external temperature at peak times during one day. The *DTmax*, given in degree units (K), is a measure mainly useful in conditions when indoor cooling is the design target. Unlike the *TSR* the *DTmax* provides a direct indication of the internal temperature if the external maximum is known. For example, on a day where the maximum temperature reaches 35 °C a *DTmax* of value of 10 will directly indicate that the temperature inside the building will remain below 25 °C all the time. Like the *TSR*, the *DTmax* allows the comparison between buildings regardless the location or the season.

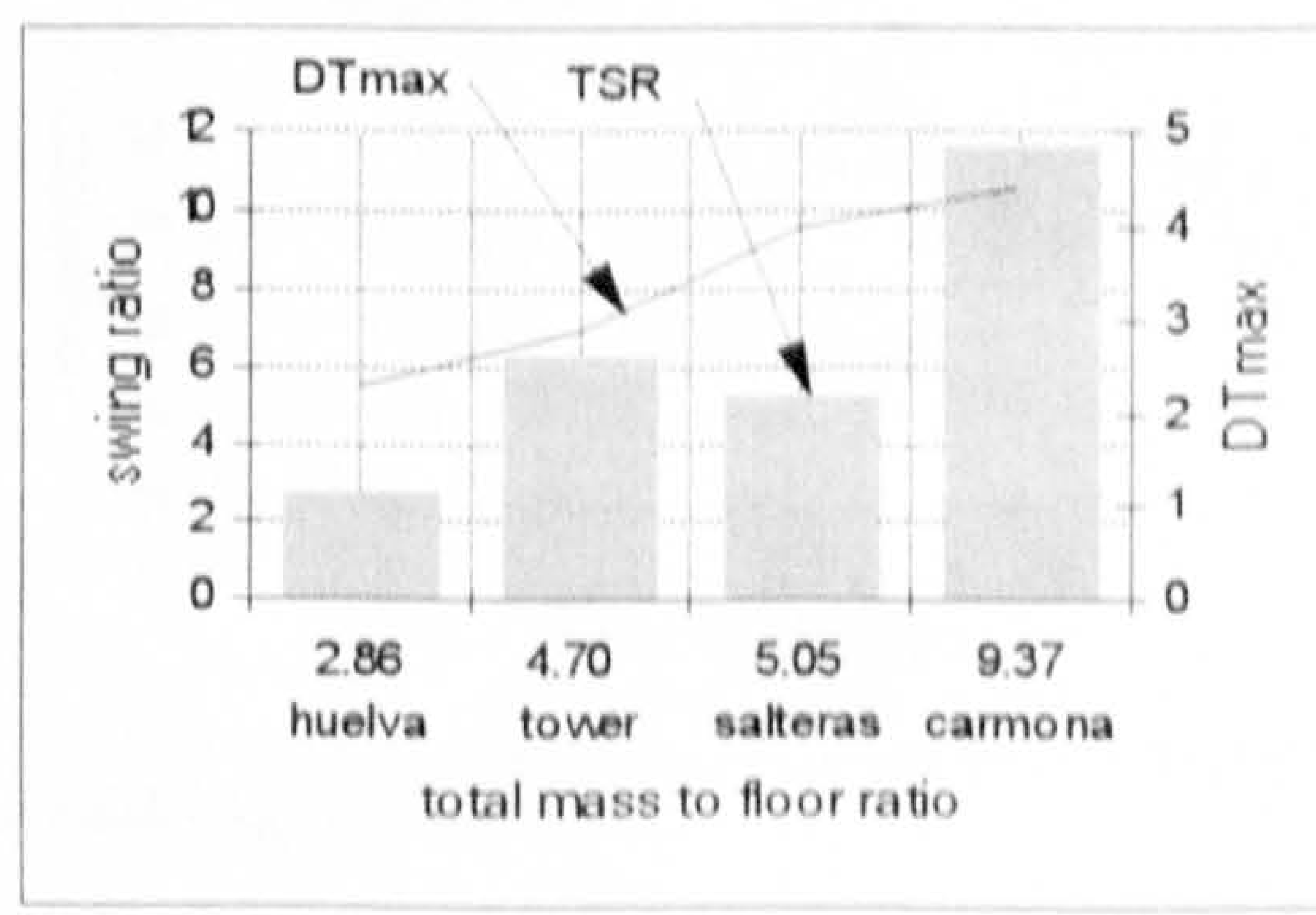
5.6.5 Interpretation of Results

The charts in 5.37 summarise the analysis of results on the effect of thermal inertia on the internal conditions of the four studied buildings. The graphs present the thermal mass parameter considered such as capacitance or mass exposure plotted against the temperature swing ratio and the peak temperature difference for each building. The thermal mass parameter is shown on the (x) axis while the *TSR* (column) and *Dtmax* (line) use the vertical axis on both ends of the graph. The effect of quantity of thermal mass was studied from the thermal capacitance calculated for all the components for each building. The results of this parameter indicate that the temperature swing ratio increases with quantity of thermal mass (columns) but quantity does not necessarily reduce the peak internal temperature (line), 5.37-a. It was found that *Tower*, a heavier building than *Salteras*, recorded smaller variations of internal temperature although internal temperatures were relatively higher than those of *Salteras*. *Salteras* however has a higher mass to floor ratio value than *Tower* and in this respect a linearity can be observed with the rest of the buildings, 5.37-b. As to *Carmona* and *Huelva*, the correlation appears to apply in both aspects, i.e. the higher the thermal capacitance and the *MFR* value, the higher the *TSR* and *Dtmax*.

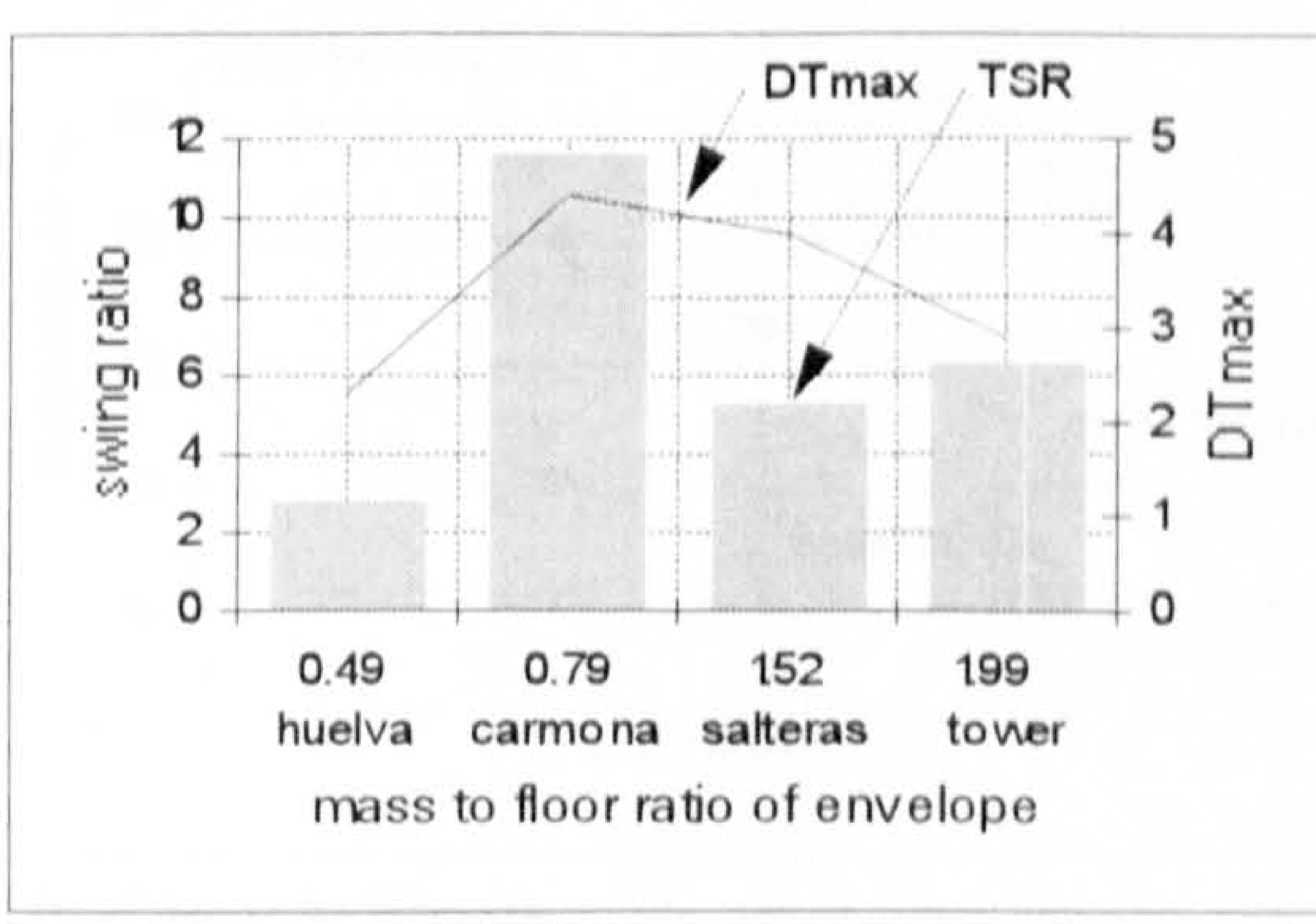
The effect of distribution and location of thermal mass was studied by plotting the mass to floor ratio of external and internal elements separately with the swing ratio and the *Dtmax*. From this analysis it was found no correlation between exposure of external mass elements and the *Dtmax* or the *TSR* in the four buildings, 5.37-d. This indicates that the greater temperature attenuation effect is produced by the internal mass elements. Graph 5.37-d shows a direct linearity between the mass to floor ratio of internal elements and the *Dtmax* and three of the four buildings also indicated a correlation with respect to the *TSR* value. The case of *Salteras*, as in the study of exposure of the total surfaces in 5.37-b, breaks this linearity. The *TSR* value of *Salteras* is smaller than that of *Tower*, i.e. the internal temperature fluctuates more despite its higher mass to floor ratio. This is probably due to the effect of the two south facing windows which were not totally shaded during the period of experiments.



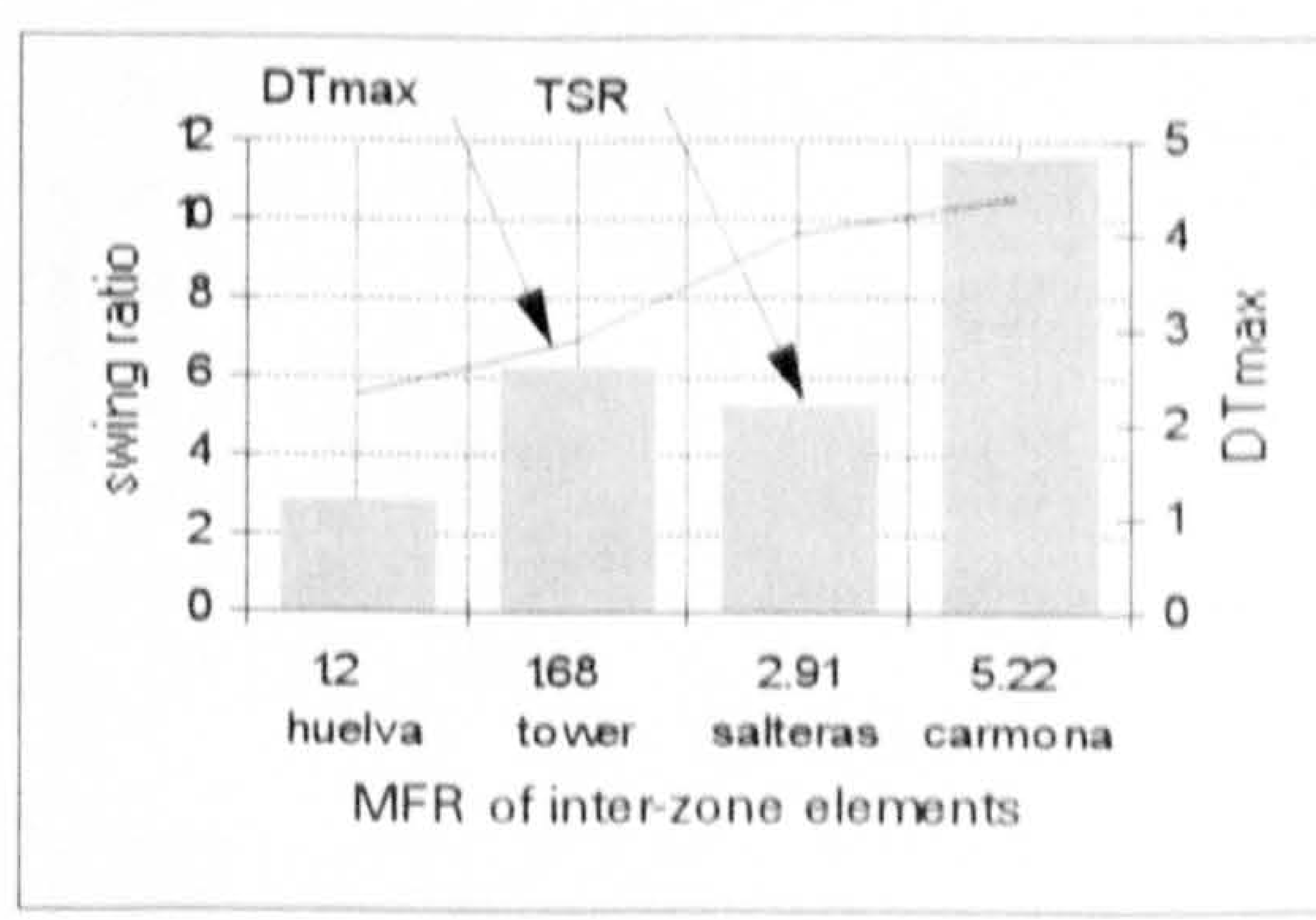
a) quantity of thermal mass



b) exposure of thermal mass



c) distribution and location of thermal mass



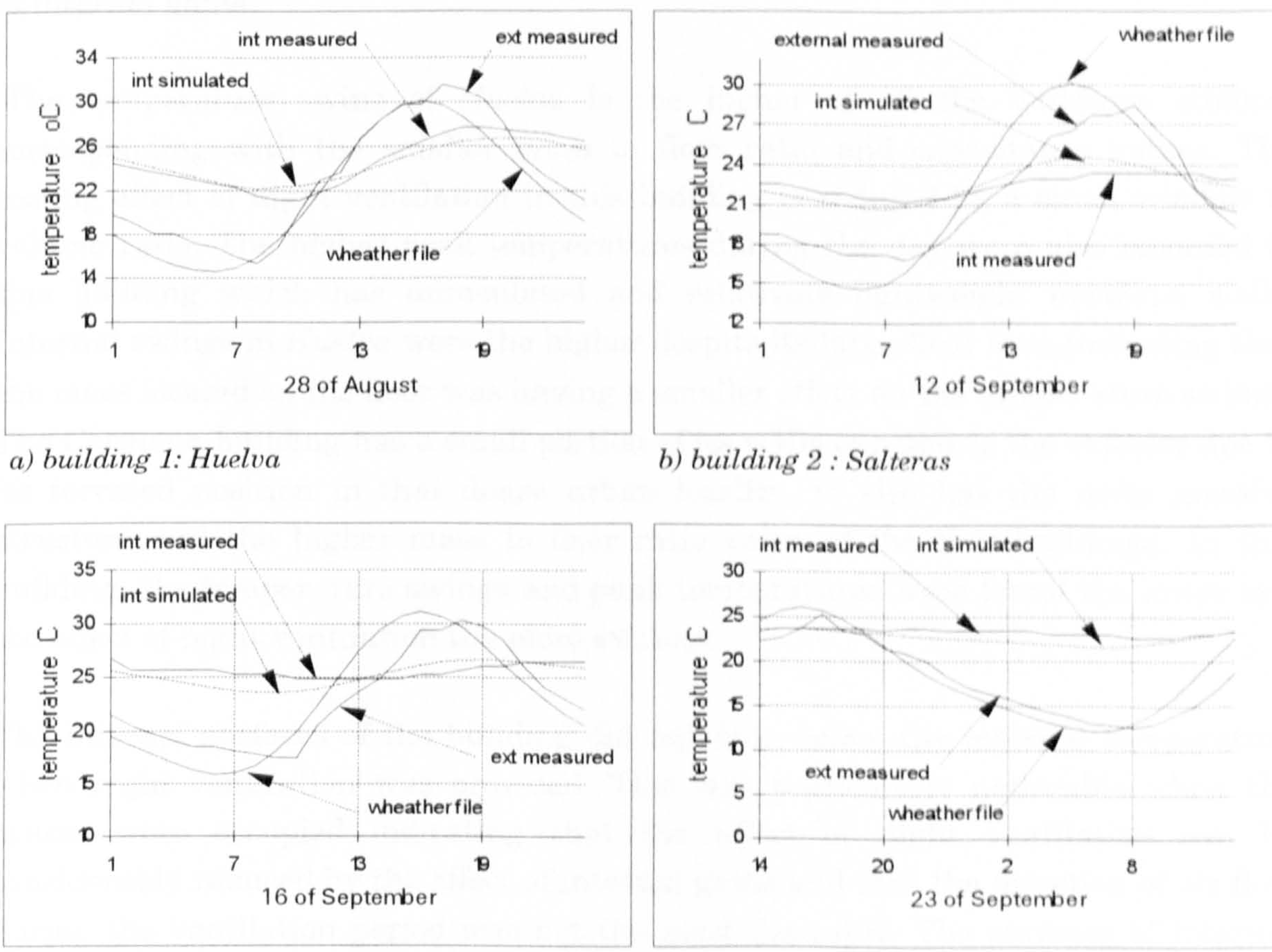
d) distribution and location of thermal mass

5.37 Effect of the thermal inertia of the case study buildings on internal temperatures

5.7 Comparison with SERI-RES Predictions

As part of the analytical work on the case studies, the results of the thermal measurements were compared with thermal simulations for each building using the computer program SERI-RES. The constructional characteristics of the zones used for the experiments were introduced into the program and predictions of hourly internal temperatures were estimated using average weather data for Seville.

The measurements of the external temperature correlated fairly well with the average weather data for Seville introduced into the program. This is particularly true for the cases of Huelva and Carmona, although for Tower and Salteras a shift in time between the occurrence of maximum and minimum temperatures can be observed. This difference was reproduced on the resultant internal temperature curve from the simulations for these two buildings. The correlation with temperature swings and mean temperatures is very good in the four cases. The use of SERI-RES for thermal simulations on a reference zone is discussed in chapter 6.



a) building 1: Huelva *b) building 2 : Salteras*

c) building 3: Tower *d) building 4 : Carmona*

5.38 Comparison between temperature data from field measurements with SERI-RES simulations for the case study buildings.

5.8 Conclusions

The results from the monitoring experiments suggest that if solar gains are minimised, the distribution and exposure of mass within the building can have a more significant role in the improvement of internal conditions than the quantity of thermal mass alone. The performance of thermal mass may be neutralised by the effect of heat gains through the structure of uninsulated elements or by excess internal gains.

The effect of thermal mass of the buildings have to be measured in relation to the heat gains. The effect of thermal inertia of the building mass may be reduced by inadequate dissipation of heat gains. Results in the *Tower* building indicated that a massive envelope may not be sufficient to reduce internal temperatures if it is not protected and if the mass to floor ratio of the room is not adequate especially with the additional effect of internal gains. In *Salteras,* the insulated envelope and the mass to floor ratio provided temperatures between 23 °C - 26 °C even with the effect of internal gains.

The temperature swing of *Huelva* is the higher of all the buildings studied, corresponding with the smaller mass to floor ratio and capacitance values. The cooling effect of night ventilation in this building is reduced by a small window to volume ratio. The higher peak temperatures during the day were also recorded in this building which has uninsulated and relatively lightweight envelope walls. Internal swings in *Huelva* were the higher despite its large floor area indicating that the mass located on the floor was having a smaller effect on the temperature swings. The *Carmona* building has a small portion of its walls exposed to the exterior due to its terraced position in that dense urban locality. It also has the more massive structure and the higher mass to floor ratio value of the four buildings. In this building, the temperature swings and peak temperatures were found the lower and the effect of night ventilation the more evident.

The internal surfaces of the building did not drop below the internal temperature when night ventilation was provided. This was particularly noticeable when the spaces were occupied indicating that the effect of night ventilation can be considerably reduced by the effect of internal gains and that the direction of air flow during the ventilation period was not the most desirable. The surfaces of internal partitions positioned away from the windows experienced the smaller variations of temperature.

Part III

Analytic Studies

6

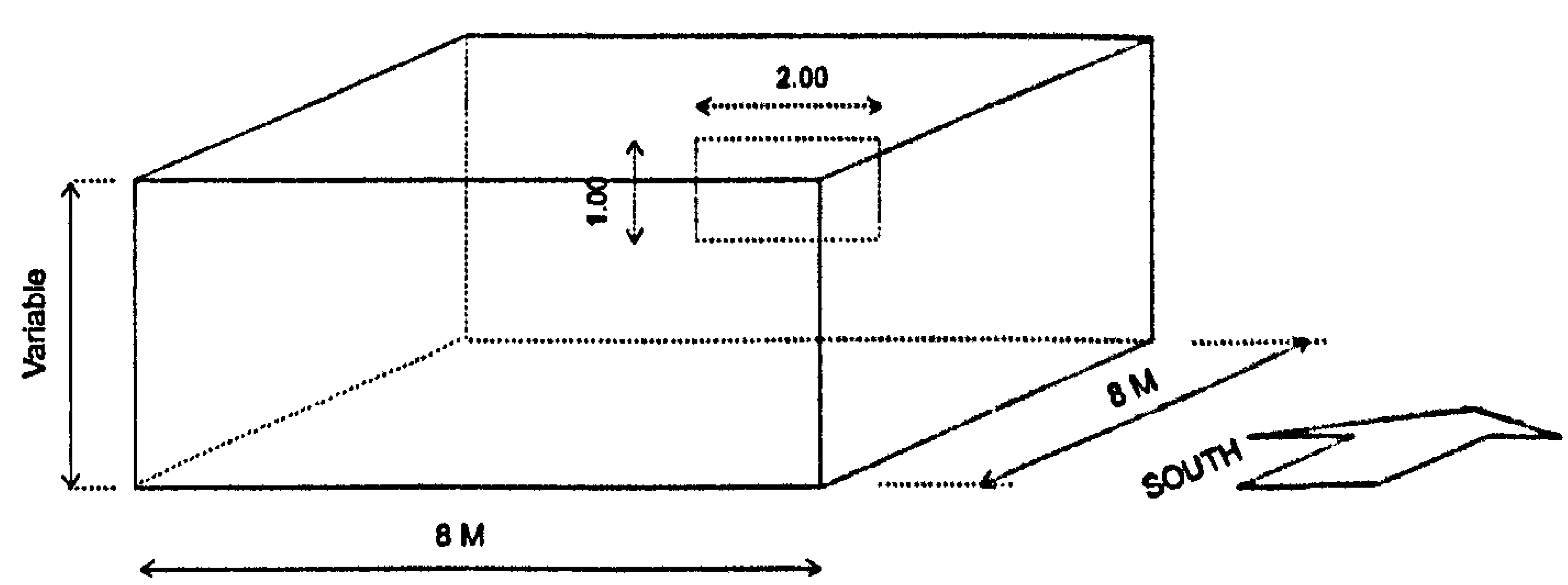
Parametric Studies on Thermal Inertia

6.1 Introduction

This chapter discusses the results obtained from a series of thermal simulations aimed at studying the effect of the thermal mass on the internal temperature of a single-zone space. The study was conducted with the use of the computer program SERI-RES and the runs were performed using weather data for Seville in August. The analysis is centred on the aspects of quantity, location and distribution of mass within the enclosure. The parametric simulations included the study of the effect of external climate and the effect of internal gains separately. The two categories were subject to simulations for a wide range of thermal mass variables.

6.2 The Reference Zone

The reference zone used for the simulations was modelled as a 64m^2 (8 x 8) enclosure with a homogeneous concrete structure for the envelope and a fully shaded 2 m^2 window on the south wall. The area of walls and thickness of the structure varied according to the parameters considered in the analysis. The simulations were carried out using two variants of the reference zone. The exposed variant allowed to study the effect of solar gains through the structure and the insulated type helped to observe the reaction of the internal mass to the effect of internal gains. The exposed zone type was modelled as an isolated enclosure with all walls and roof exposed to the outside. The assumption here is that the structure will be sensitive to the effect of solar radiation. In these runs, the structure varied thickness but was maintained uninsulated. The second zone type was modelled as a perfectly insulated space.



6.1 Reference zone used for simulations

6.3 Plan of Simulations

The plan of simulations for the thermal mass variables adopted the strategy used in the previous section, where the three categories of study, the quantity, the location and the distribution of thermal mass were measured against the *TSR*[1] and the *DTmax*[2]. In this way, the comparison between the parametric simulations and the measured data from real buildings was possible. Table 6.1 presents a summary of the plan of simulations performed.

Table 6.1

Simulations Strategy for Thermal Mass Studies

Thermal Mass Category	*Zone Type*	*Parameter Varied*	*Objective*	*Observations*
quantity of mass	exposed and insulated	thickness of envelope	identifying optimum envelope thickness	
exposure of mass	exposed	*MFR*[3] of envelope	effect of envelope area under the effect of external excitations.	
	insulated	*MFR* of envelope	effect of envelope area under the effect of internal gains.	
	insulated	*MFR* of internal partitions	effect of area of double exposed surfaces.	
distribution of mass	insulated	wall and roof thickness and *MFR*.	the optimum distribution of mass within the zone.	The *MFR* to floor ratio was altered keeping the same volume of mass (128 m^3).
location of mass	exposed	placement of mass slab.	to identify the most sensitive location of thermal mass within the exposed zone.	A 1M concrete slab was placed on each element of the zone structure for each run.
orientation of exposed wall	insulated	orientation of exposed wall.	to test sensitivity of the exposed wall in the insulated zone.	The wall used as the exposed front wall varied orientation for various *MFR* values.

1. *TSR* = temperature swing ratio ($\Delta T_o/\Delta T_i$), (where ΔT_o = external temperature swing)

2. *DTmax* = peak temperature difference = $T_{o(max)} - T_{i(max)}$

3. *MFR* = mass to floor ratio ($\Sigma A_i/A_f$), (where A_i = area of internal surfaces, A_f = floor area)

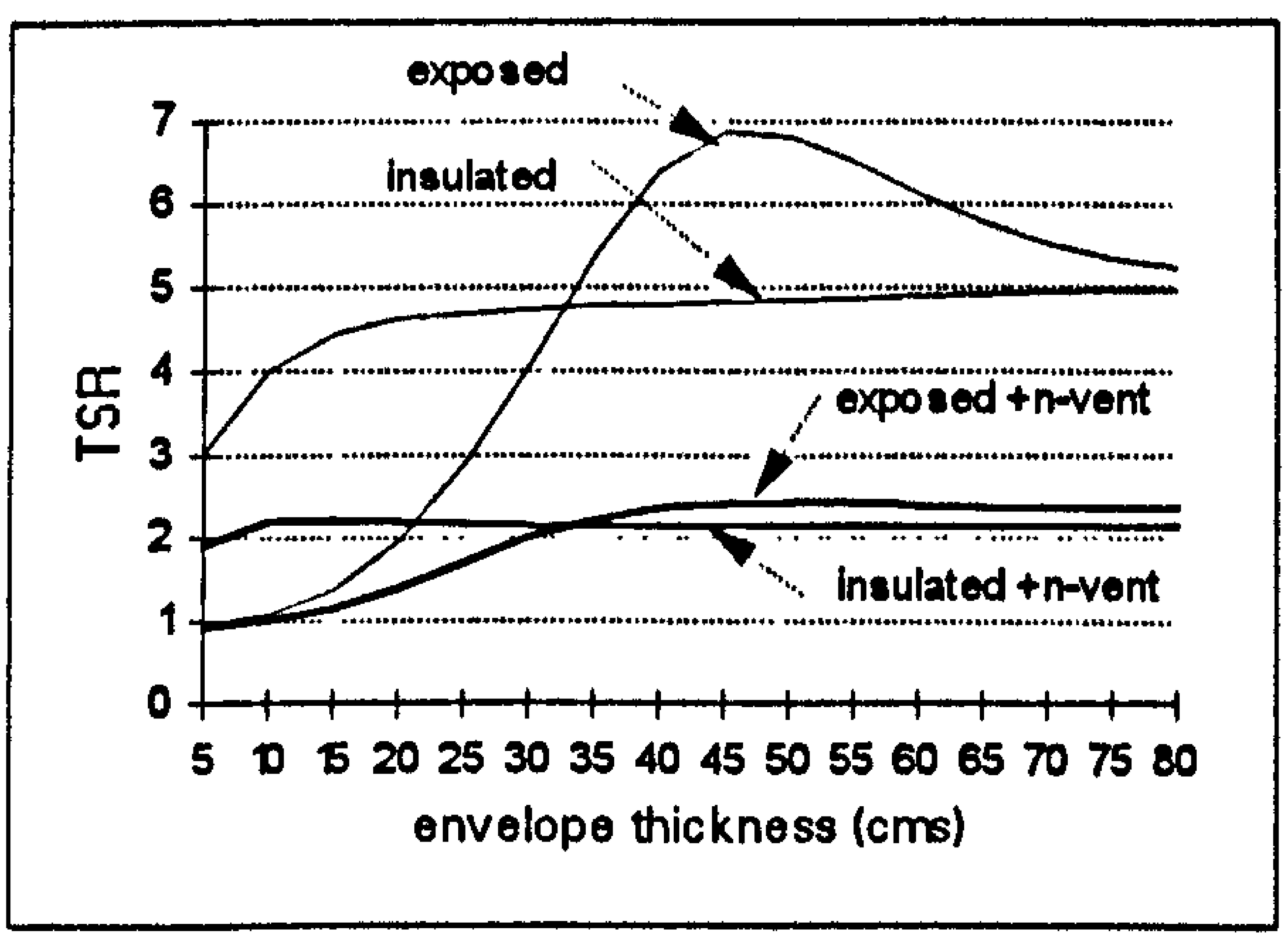
6.3.1 Ventilation and Internal Gains

The simulations for the unventilated zone type were carried out assuming a ventilation rate of 1 ac/h. The effect of night ventilation was introduced into the analysis by selecting the most relevant features found in the unventilated zone types and performing the same simulations with an additional night-time ventilation rate of 20 ac/h. A series of ventilation simulations for a single room were conducted using BREEZE [30] and the results used here. Air change values for various opening areas, wind directions and window heights are also presented in Appendix 7. The internal heat gain rate was set at 36 kWh/day (23.4 W/m^2).

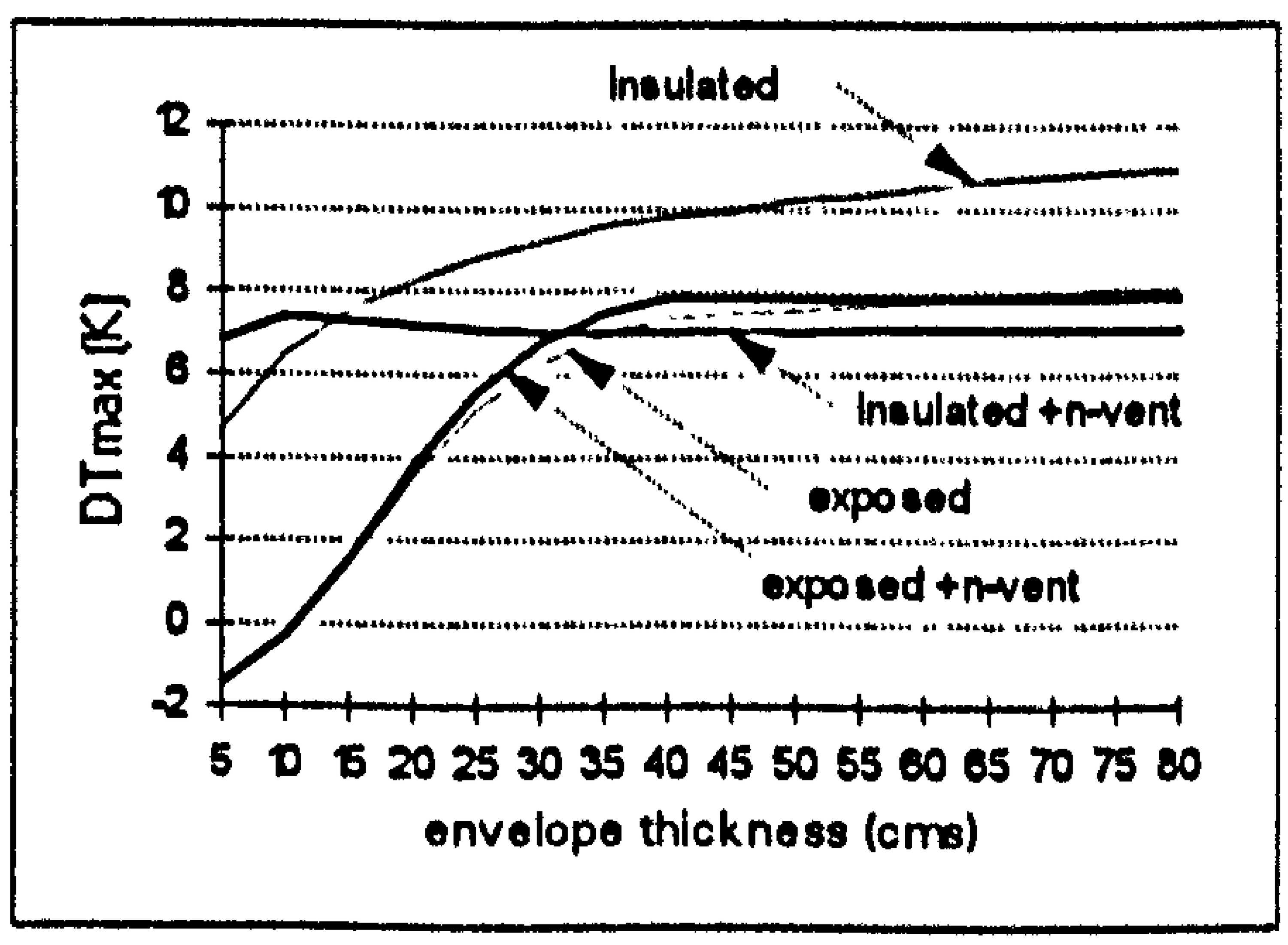
6.4 Thermal Mass Variants

6.4.1 Effect of Thickness

The first aspect examined is the effect of quantity of mass through variations of the structure thickness. The results indicated that by making the envelope thicker, both the temperature swing ratio and the peak temperature difference will tend to increase. However, beyond an optimum value further thickness will have a neutral and in some cases a detrimental effect on the thermal performance of the rooms where the *TSR* and *DTmax* will show lower values, 6.2.



a) effect of thickness on TSR



b) effect of thickness on DTmax

6.2 Effect of envelope thickness on the temperature swing ratio and *DTmax* of the reference zone showing insulated, exposed and night-ventilated variants.

The optimum thickness of the structure is determined by the condition of the envelope (insulated or exposed) and whether the space is night-ventilated or not. If the envelope of the zone is exposed to the external environment, increasing thickness of the concrete walls and roof up to 45 cm. will be beneficial since both *TSR* and *DTmax* values will tend to increase. Further thickness will make little difference on the *DTmax* and will decrease *TSR*. The same applies when night ventilation is introduced except that the *TSR* values are lower because the internal swing is increased with the effect of night cooling but the *DTmax* will be greater, indicating lower temperatures inside the zone. If the envelope of the zone is insulated, there is an apparent benefit from increasing thickness up to 20 cm. but after this point, the curves will tend to flatten down showing smaller effects. When night ventilation is introduced to the insulated zone the optimum thickness of the envelope will be further reduced to around 15 cm.

6.4.2 Exposure of Mass

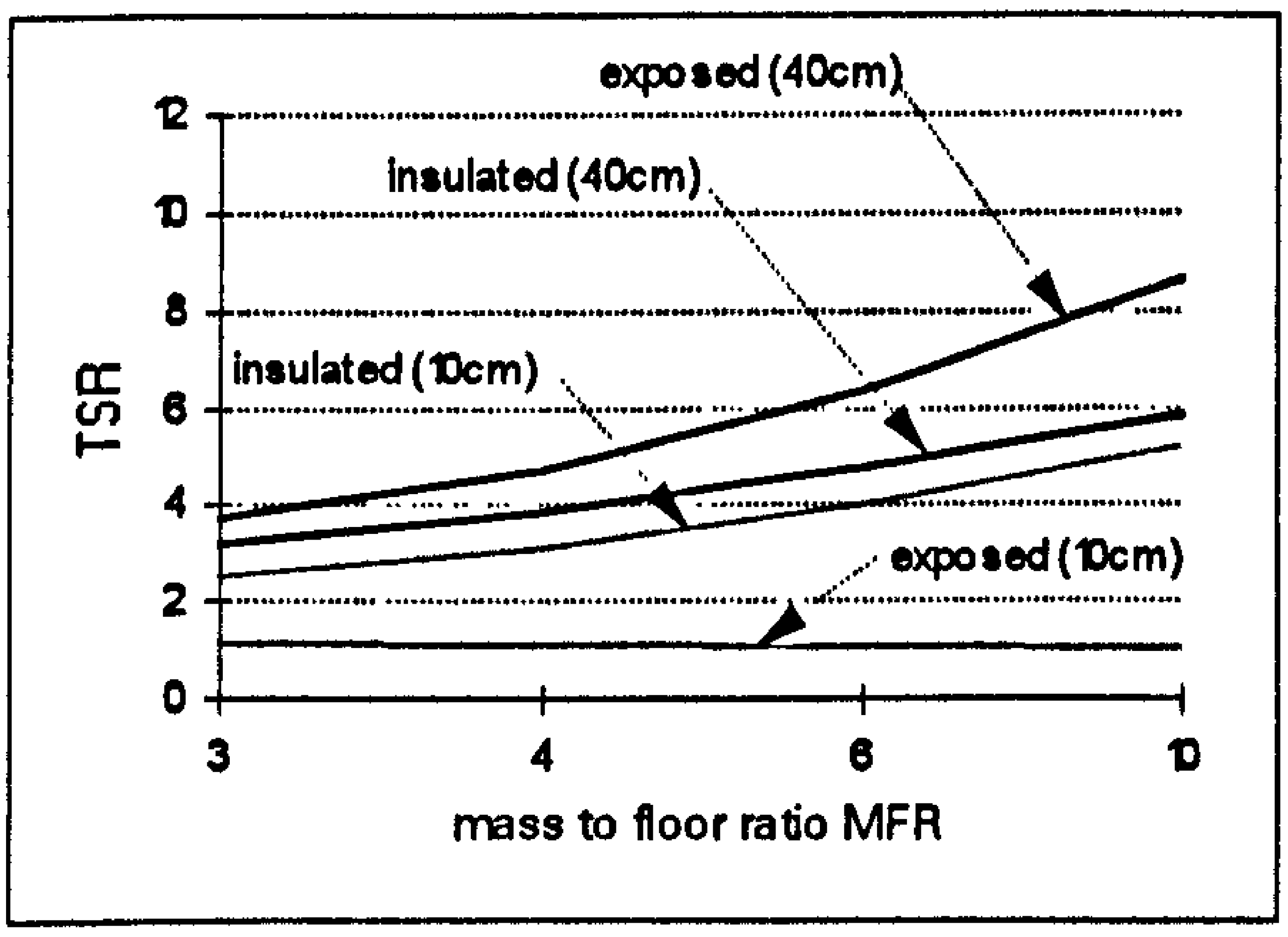
The influence of the exposure of mass was studied by altering the ratio of the heat exchanging mass surface area to the floor area of the reference zone and identifying its effect on the internal temperature. For this purpose, the parameter *MFR* was varied from 2.5 up to 10 (see table 6.2 for the corresponding proportions) and the envelope thickness varied from 0.10 to 1m. It was assumed that the zone is free from furniture and massive surfaces have no covered portions, i.e. 100% of the mass elements are exposed to the inside.

Table 6.2
Mass to Floor Ratio for a 64 m² Zone

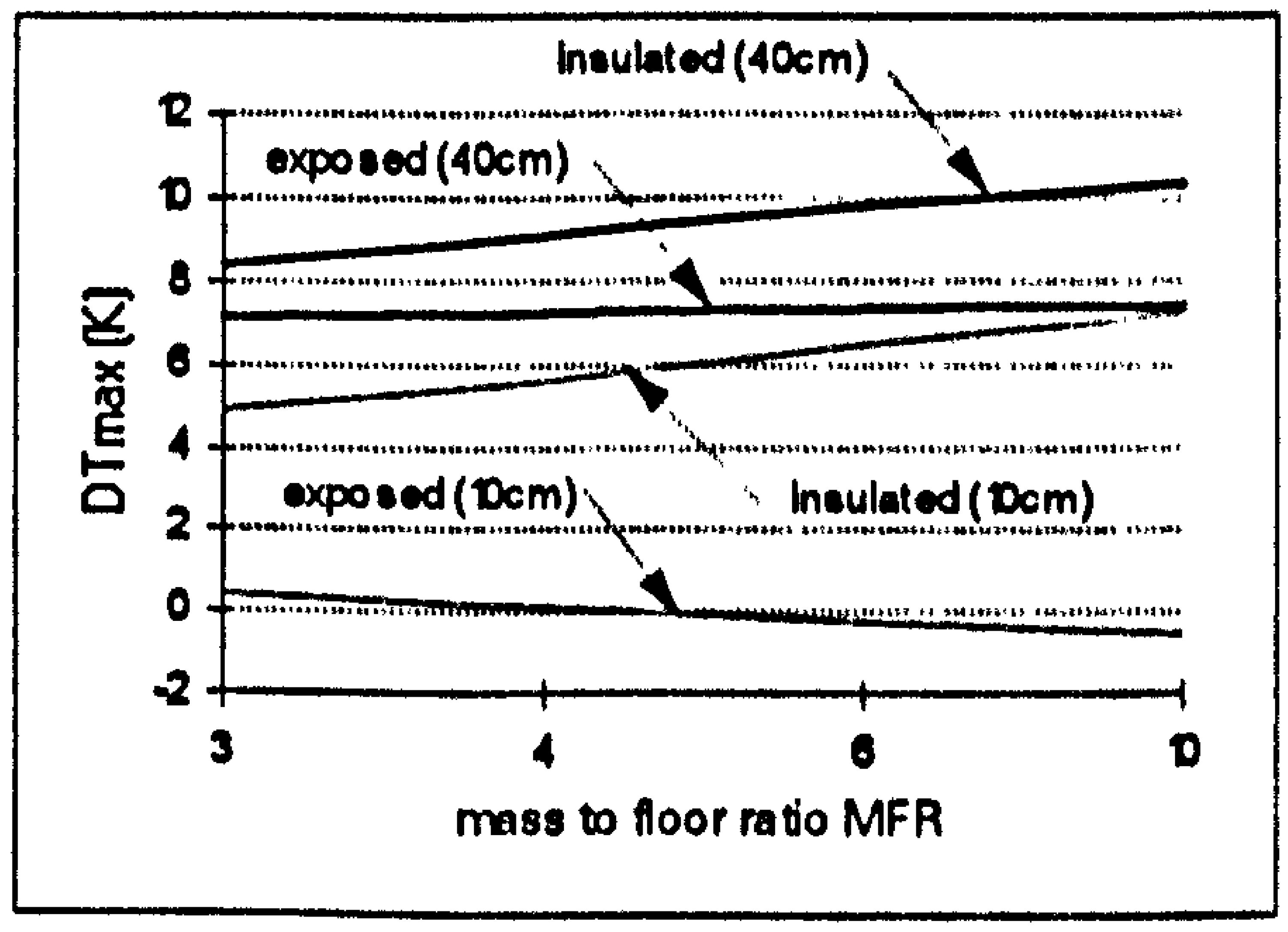
MFR Value	*Wall area (m²)*	*Wall height (m)*
2.5	8	1
3	16	2
4	32	4
6	64	8
10	128	16

6.4.2.1 Exposure of Envelope

This set of runs were performed using both the exposed and the insulated zone types. The results of the exposed type indicated that although the extent to which the room temperature reacts to variations of surface area varies with the thickness of the envelope, the increase of the *MFR* of the zone makes the internal temperature to decrease unless the envelope is 0.15m or thinner, 6.3. As the charts suggest, elevating *MFR* on zones with the lightweight structure (0.10 m), shows no improvement on the *TSR* and in fact decreases the *DTmax* value which means that the temperature inside the zone rises with large exposure due to the higher conductive heat gains through the fabric. In contrast, the results on the heavier structure where a larger proportion of heat is stored in the building mass, indicated that both internal temperature and the internal swing decrease as the area of the mass exposed is increased. For uninsulated envelopes the effect of increasing exposure will depend on the thickness of walls and roof.



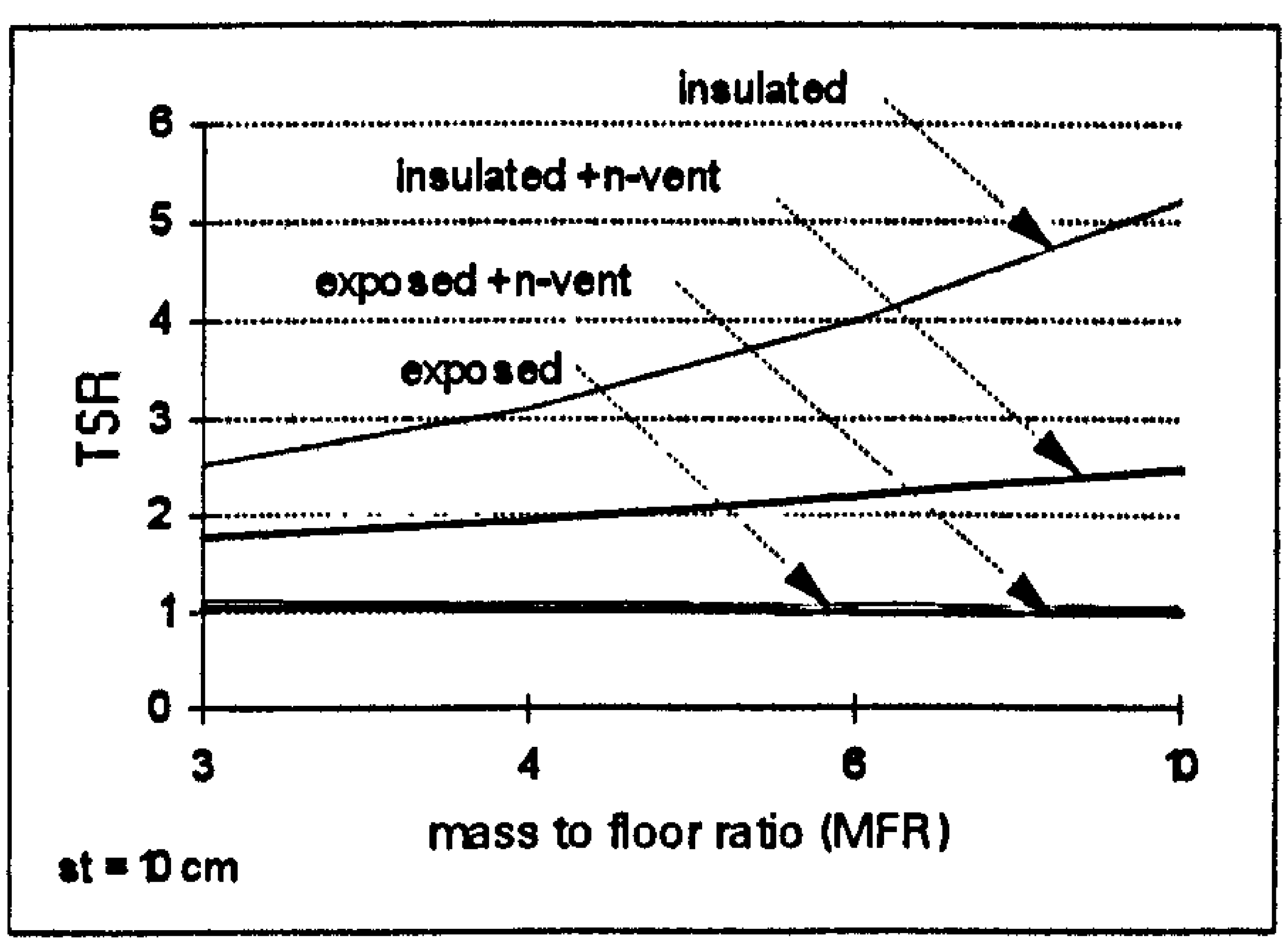
a) mass to floor ratio on TSR



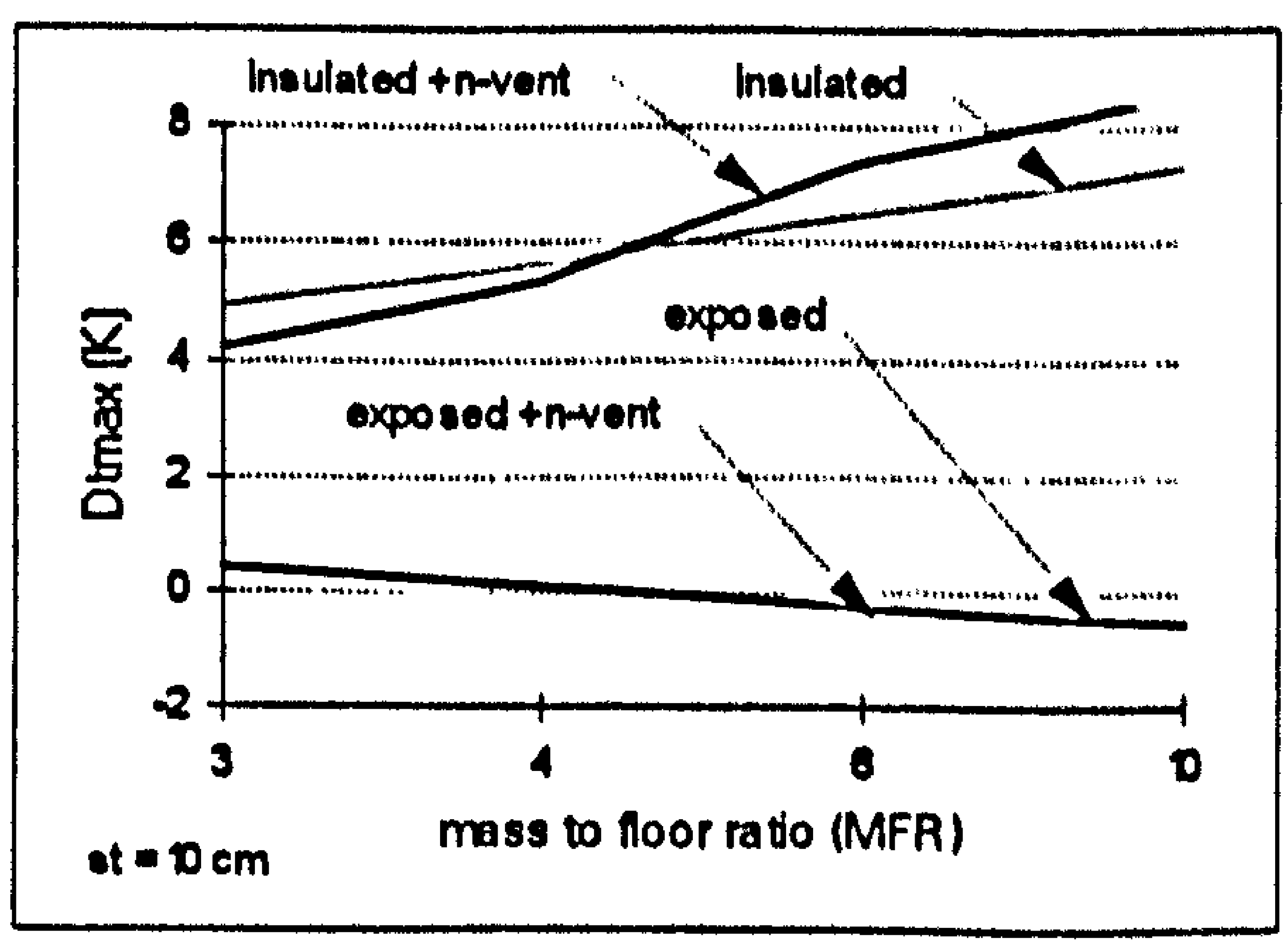
b) mass to floor ratio on DTmax

6.3 Effect of mass surface exposure of envelope walls on exposed and insulated zone types.

If the envelope is exposed to the exterior and the structure is not very heavy, e.g. a wall thickness of 10 cm. or less, increasing the mass exposure will produce an increase of the internal temperature swings despite the larger quantity of mass.
The lightweight envelope allows higher heat gains through the structure as the area of walls augments. An increased night ventilation rate in these situations will not change the outcome, 6.4.



a) effect of mass exposure on TSR



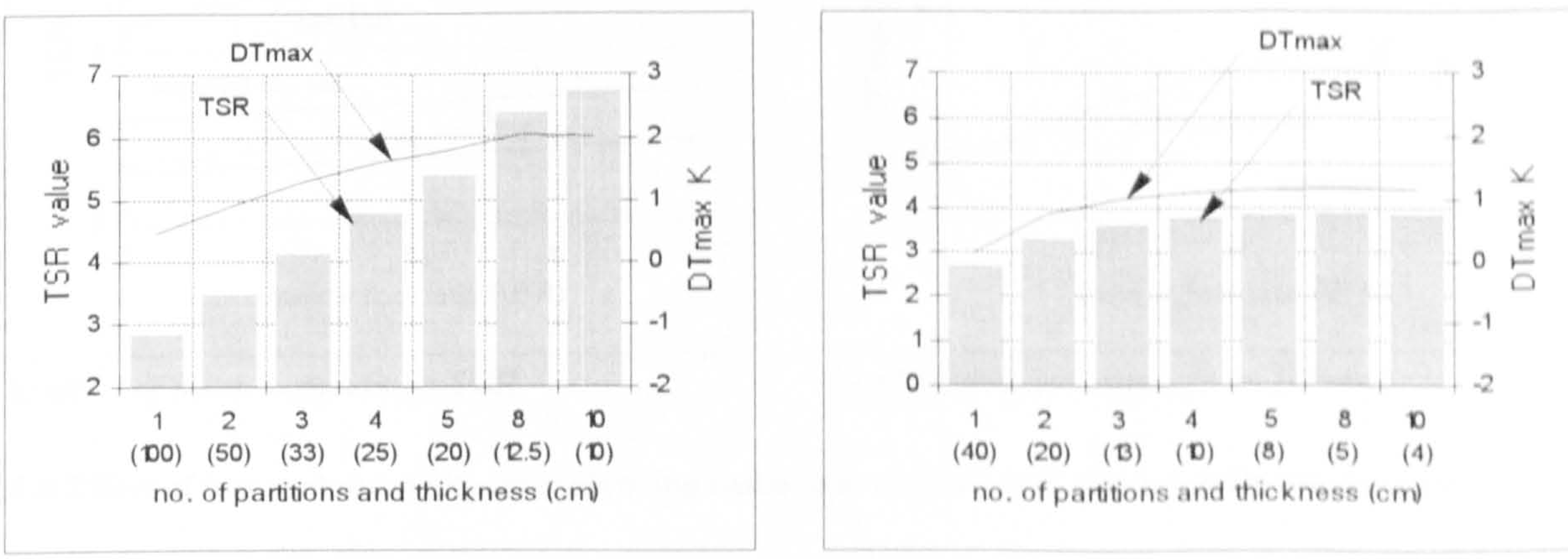
b) effect of mass exposure on DTmax

6.4 Effect of envelope exposure showing insulated, exposed and night-ventilated variants.

If the envelope is insulated, the *TSR* and *DTmax* will increase substantially with greater mass surface area regardless the thickness of the envelope. In this situation, as no heat is being conducted through the fabric, the increase of *MFR* values represents a larger storage capacity for the internal gains. If night ventilation is added the cooling effects become greater as the mass exposure increases.

6.4.2.2 Exposure of Internal Partitions

The second aspect considered within the category of mass exposure is the exposure of internal partitions. The introduction of internal partitions into the zone implied that the heat exchanging surface area is automatically doubled since the two sides of the partition are coupled with the interior of the zone. The test was aimed at comparing the effect of exposure against the thickness of internal partitions. This was carried out by placing a single partition in the reference zone and then comparing its thermal effect in the room with that of two partitions half of the thickness of the first. Subsequently, this was repeated for 3, 4, 5, 8 and 10 partitions, 6.5.

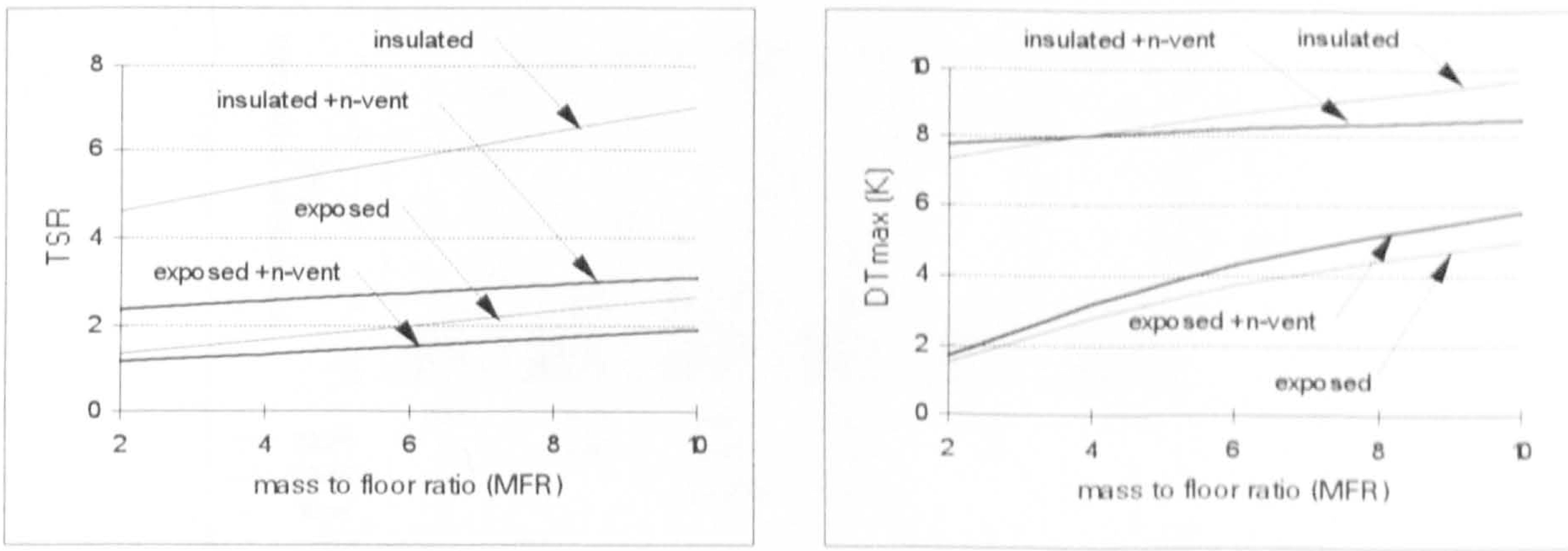


a) original thickness = 1m *b) original thickness = 0.40 m*

6.5 Effect of surface exposure of internal partitions on an insulated zone.

Various thicknesses were tested as the original partition. This helped to explore a wide range of variables regarding thickness and exposure of internal elements and also to identify the limits where increasing the exposed area of partitions change the general tendency. Most of the cases indicated that the *TSR* and *DTmax* increase if additional surface area is given to the partitions. This means that the distribution of thermal mass throughout the exposed surface rather than on the thickness of internal partitions is considerably beneficial to reduce the temperatures and the internal swings. Obviously the effect is more noticeable when larger amount of mass is subdivided, i.e. thicker partitions are doubled or trebled. However, the simulations suggested that the increase of surface area of internal partitions at the cost of thickness is only worth considering if there is sufficient thickness on the element.

The limit thickness below which an increase of exposed area of the partition would not be beneficial was around 10 cm. Increasing the surface area of thinner partitions would result in smaller *DTmax* and *TSR* values as each partition would have very low heat storage capacity. The tests on exposure of internal elements produced greater temperature swing ratio and *Dtmax* values in zones with insulated envelopes and with night ventilation, 6.6. The results of this set of simulations suggest that optimality of internal thermal mass is closely related to effective distribution and position rather than quantity.



a) effect of mass exposure on TSR *b) effect of mass exposure on DTmax*

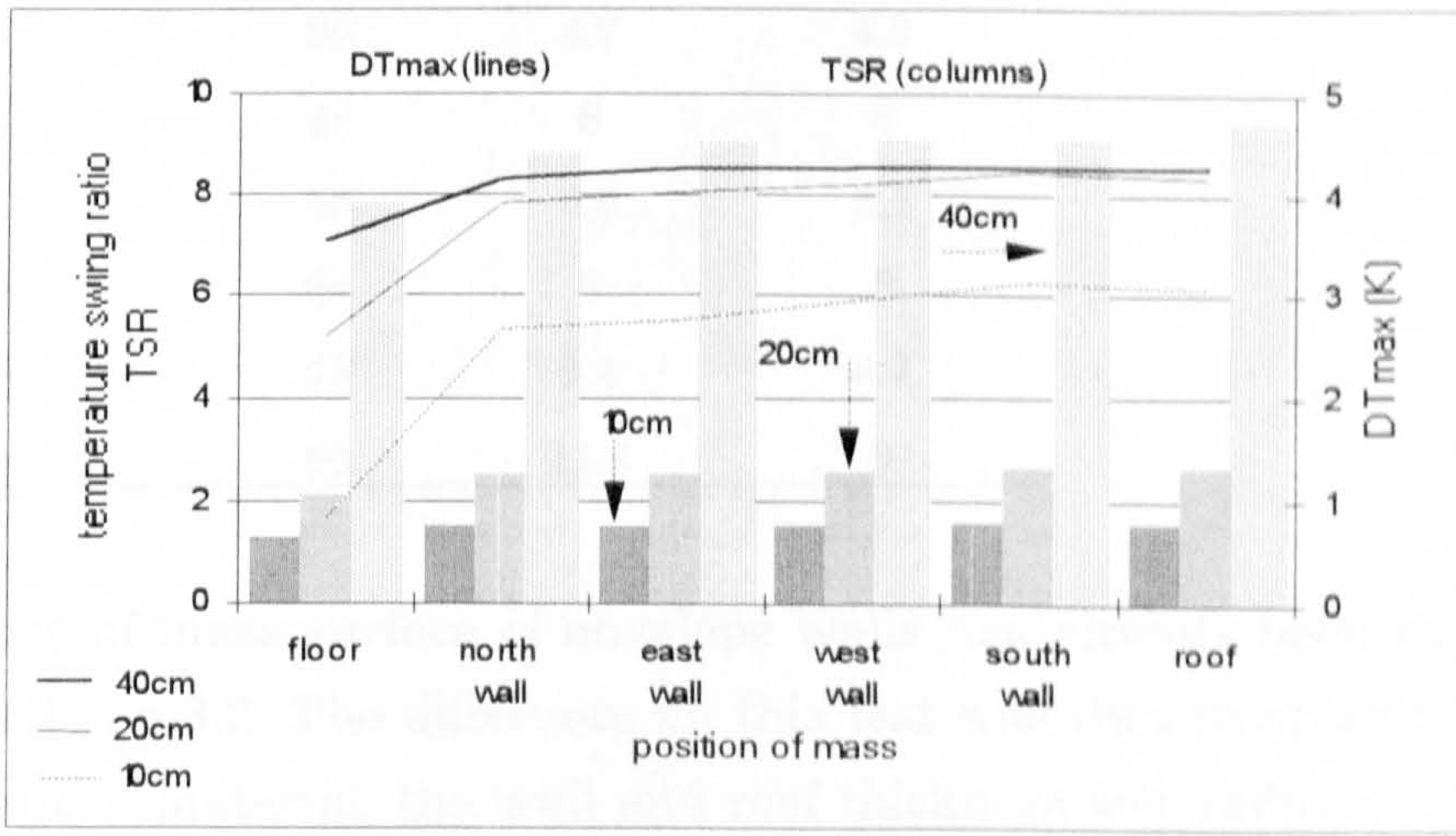
6.6 Effect of internal mass exposure showing insulated, exposed and night-ventilated variants.

6.4.3 Location of Thermal Mass

The influence of location of thermal mass within the zone was investigated through a set of simulations where a 1 m concrete slab was attached to one of the elements of the zone, i.e. the floor, the ceiling or one of the walls while the rest of the structure was kept with its original thickness. The effect of location of mass within the zone in this section was tested for the exposed zone variant and the structure of the zone varied from 0,10 m to 0.40 m thick. The horizontal axis on the graphs indicates the element of the zone where the heavy slab was located and its impact on the temperature swing ratio (columns) and the peak temperature difference (lines) for three different thicknesses, 6.7.

The difference in internal temperature conditions obtained by altering the position of the thermal mass from one element to another is more apparent as the structure of the zone becomes lighter. The lightweight zone (10 cm) shown with the dotted line (*DTmax*) and the dark column (*TSR*) on the chart indicate smaller values on all positions compared to the heavier zones.

On the heavier envelopes the influence of mass position become less significant, however, despite the small differences, it can be noticed that all the curves agree to indicate the south wall and the roof where the position of mass is more effective. The position of thermal mass on the floor also shows in all the cases a smaller impact on the thermal conditions of the space.



6.7 Effect of location of mass on the temperatures of the exposed reference zone.

6.4.4 Distribution of Thermal Mass

This test was aimed at identifying the most efficient distribution of thermal mass within the reference zone. The test consisted of distributing the same amount of thermal mass in various zones of different sizes with the same floor area (proportional distribution). In this way, the parameters that changed were the *MFR* value and the thickness of walls and roof but the overall thermal capacity of the zone remained unchanged. This test was performed with the exposed zone type.

A concrete enclosure with a 0.60 m thick envelope and a 0.10 m thick floor was used for the initial zone. The floor thickness was kept at 0.10 m in all the cases due to the less influential role of thermal mass on the floor indicated by previous tests. A total 134.4 m^3 of thermal mass (concrete), 128 m^3 for the walls and roof and 6.4 m^3 for the floor slab, was distributed throughout the envelope of the zones altering the wall areas and the thickness of walls and roof on each run. The corresponding values for each zone are listed in table 6.3.

Table 6.3

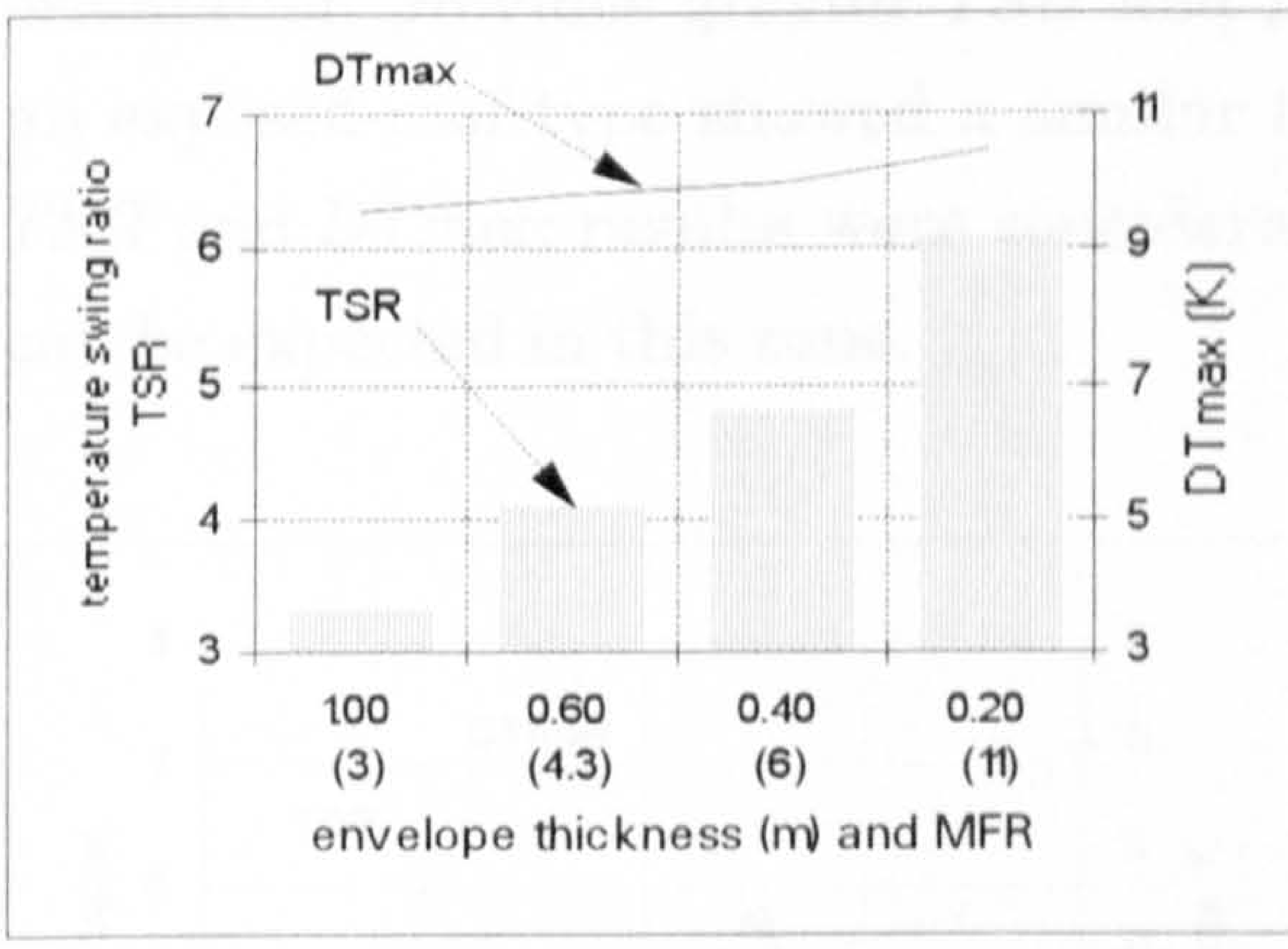
Thermal Mass Distribution Values

Envelope Thickness (m)	*Wall Area (m^2)*	*Wall Height (m)*	*MFR*
0.60	38	4.7	4.3
0.50	48	6	5
0.45	55	6.9	5.4
0.40	64	8	6
0.35	75	9.4	6.7
0.30	90	11.3	9

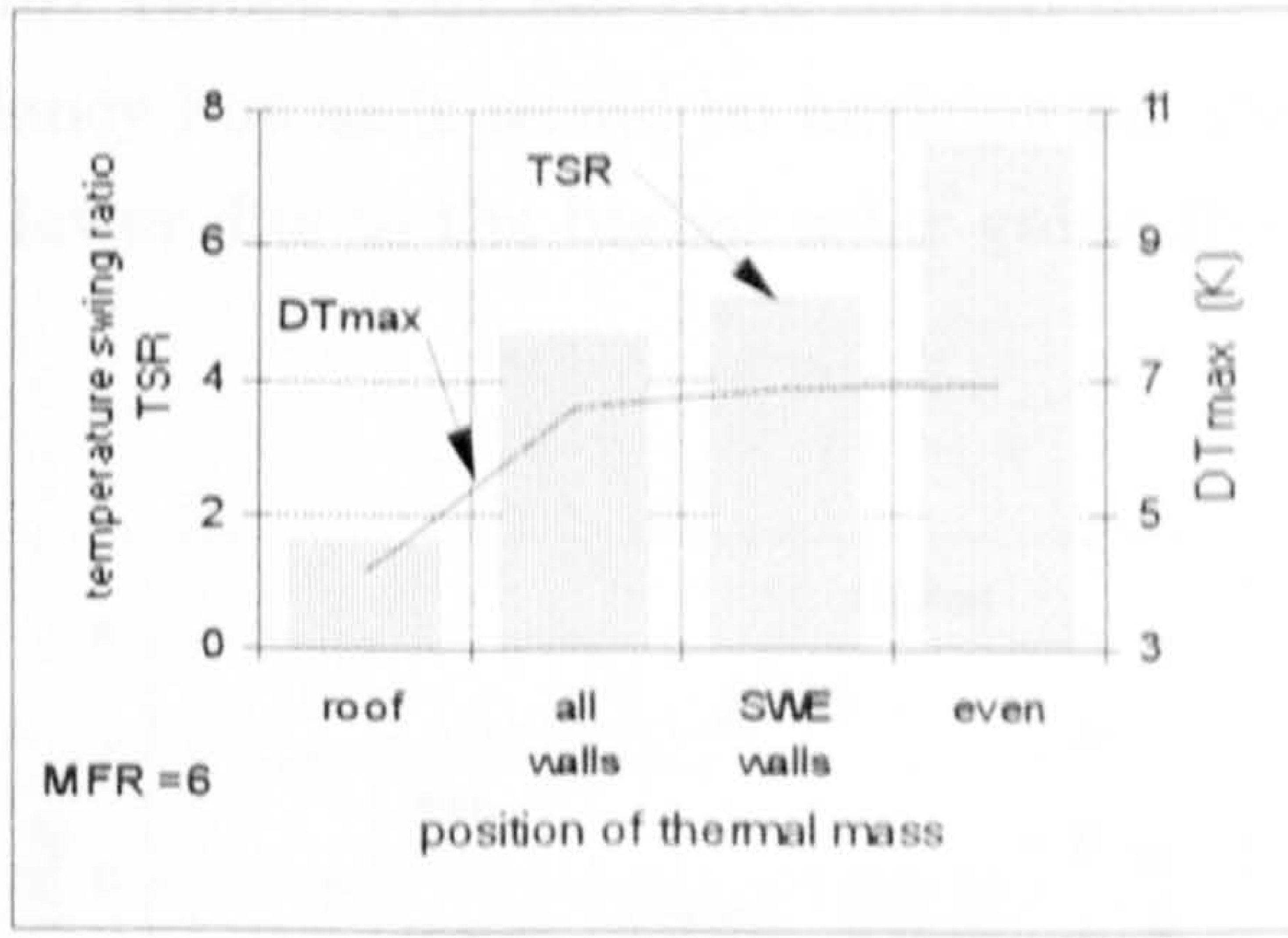
The exposure of mass surface of envelope walls has already been discussed in the tests on section 6.3.2. The difference on this test was that in order to maintain the same amount of material, the wall and roof thickness was reduced in proportion to each increase of wall area, (proportional distribution). The results clearly indicated that if the enclosure is subject to heat gains through the envelope, the thickness of the structure prevails over the exposure of the surfaces in attaining greater *TSR* and *DTmax* values, 6.8.a. Like in the previous tests on envelope exposure, this result was expected since the total heat gain in the room will increase as the area of the envelope increases and even more if the wall and roof thickness is reduced.

A second task as part of the mass distribution test was to assign different thickness to each of the elements concentrating a larger portion of thermal mass on a selected position (selective distribution), 6.8.b. The elements on which the greater portion of thermal mass was concentrated are indicated on the horizontal axis. The column read as *SWE-walls* indicate that the mass was distributed between the south, east and west walls. The column labelled *even* indicate that the thickness of the walls and roof were all the same. The results of the test showed that the *TSR* and the

DTmax reached their higher values when the concrete is distributed uniformly throughout the zone. This suggests that if the thermal mass is concentrated on individual elements of the zone however massive these elements may be, the rest of the structure will not have adequate storage capacity and the overall effect of the thermal mass of the zone will be reduced.



a) Proportional Mass Distribution. As the MFR increases, the thickness decreases proportionally.



b) Selective Mass Distribution. Mass concentrated on one of the positions indicated.

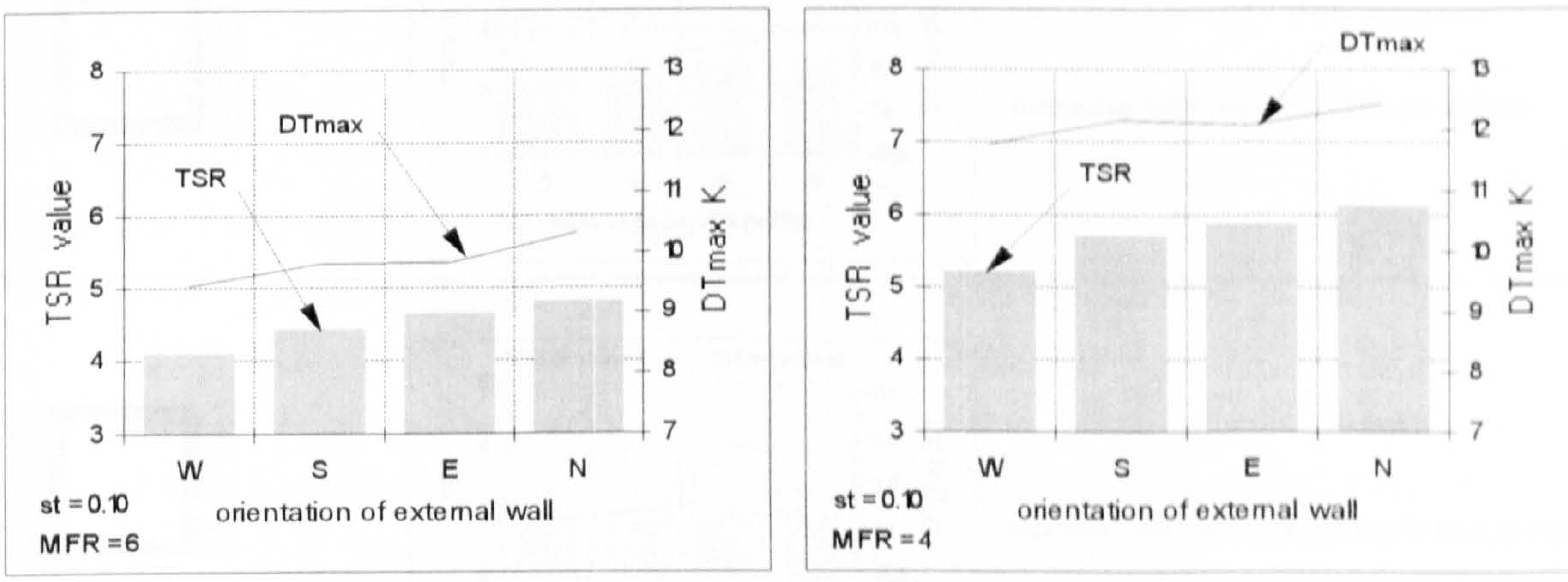
6.8 Distribution of mass on the insulated zone types.

The temperature swing ratio and *DTmax* values of the insulated zone increased as the portions of thermal mass taken from the envelope thickness were proportionally distributed throughout the walls and roof. The highlighting feature of this exercise was that the thermal mass used for the thick envelope was more efficient when re-distributed proportionally into thinner walls and roof with greater surface areas. This helped to reduce the internal temperature as illustrated on the example in 6.10-a. In the exercise on mass distribution shown in graph 6.10-b, the best results were obtained by distributing the thermal mass evenly throughout the zone rather than concentrating it on a particular element.

6.4.5 Orientation of External Wall

A wide range of simulations were performed to study the effect of orientation on the internal temperatures of the reference zone. This test was carried out with the insulated zone type with the additional variant that one of the walls was left un-insulated and in contact with the exterior. The exercise was aimed at identifying the orientation on which the external wall was more sensitive to variations of thermal mass. The test combined the effect of thickness and area of the external walls for four orientations, 6.9.

The charts indicate that the effect of varying the orientation was more significant in light structures than in heavy mass envelopes. Similarly, the *TSR* and *DTmax* of the zone increased with lower *MFR* values. These two observations suggest that the effect of orientation is related to the amount of solar gains conducted through exposed walls. Although not substantial, there is a clear indication that the north orientation provides greater *TSR* and *DTmax* values. Further runs carried out for an exposed-roof type showed a similar tendency but as it would be anticipated, the *TSR* and *DTmax* results were considerably lower due to the higher solar gains that can be expected in this zone.



a) envelope : 0.10 m, MFR = 6

b) envelope : 0.10m, MFR = 4

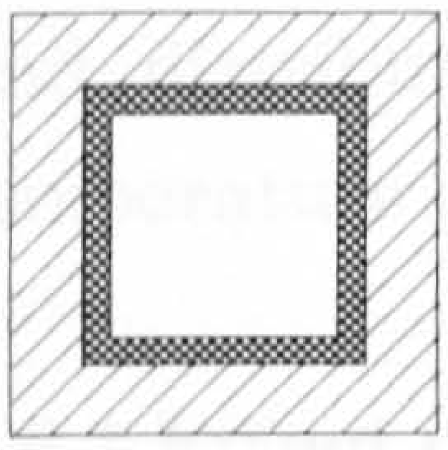
6.9 Effect of orientation on the *TSR* and *DTmax* of the reference zone.

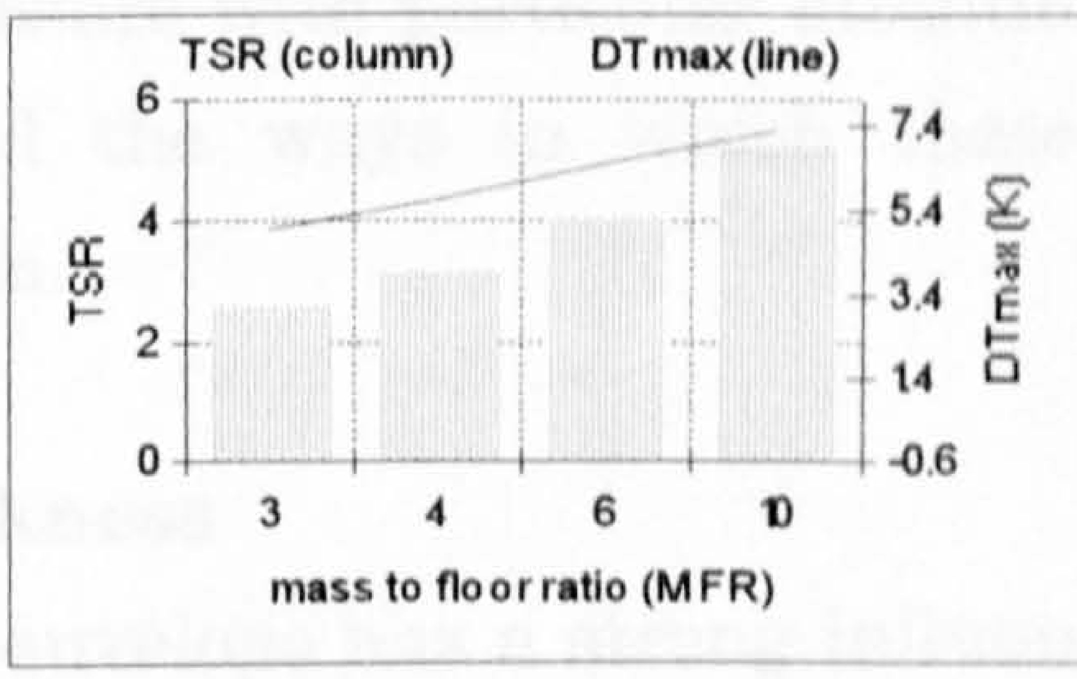
The weight of the building structure determines the effect that orientation of the external wall may have on the interior. Massive envelopes minimize the effect of altering orientation since less heat is conducted through the fabric into the zone. For lightweight envelopes the north orientation produced the higher *TSR* and *DTmax* values because the amount of incident radiation on the north side is the smaller and the conducive solar heat gains are reduced.

6.5 Effect of Other Variations to the Reference Zone.

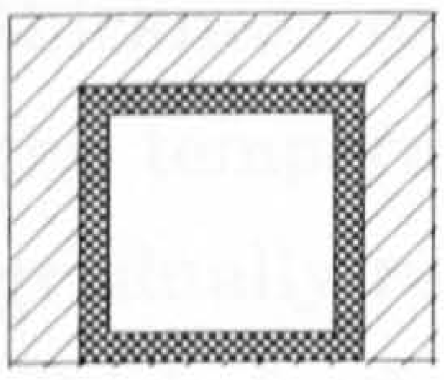
In addition to the insulated and the uninsulated zone types further results were obtained from other variations showing the tendencies of intermediate conditions. These included zones with two walls insulated and two exposed, with all walls and roof insulated, and with one wall insulated and three exposed. The results of these runs are shown in the matrix.

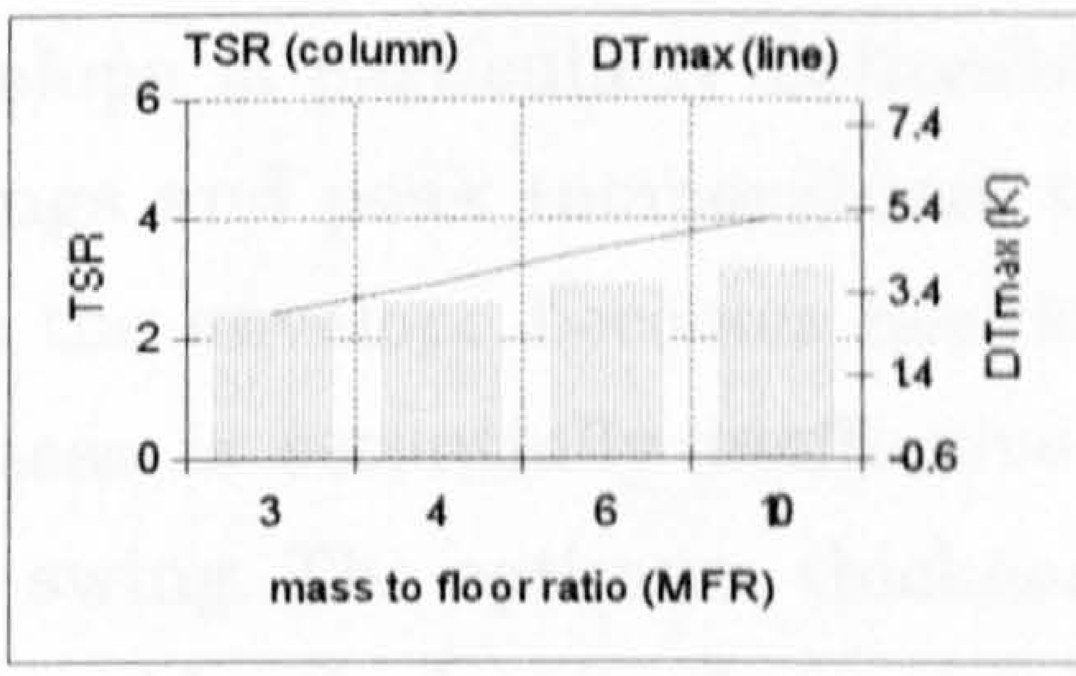
zone variant *effect of MFR on TSR and DTmax* *observations*



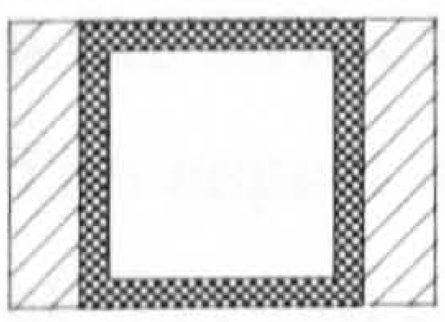


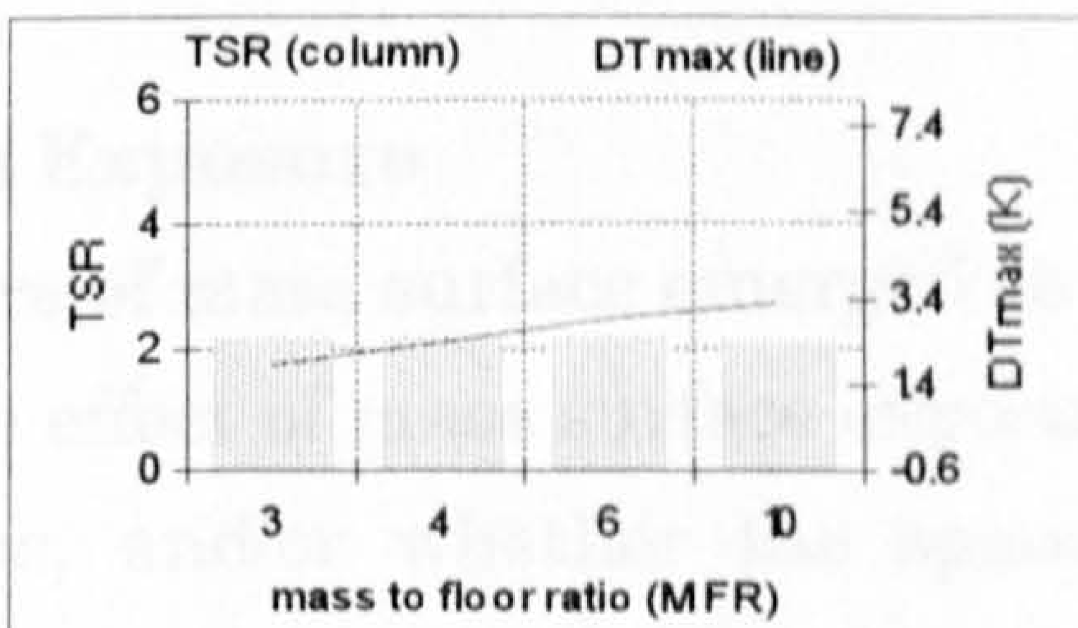
increasing *MFR* improves *TSR* and *DTmax*



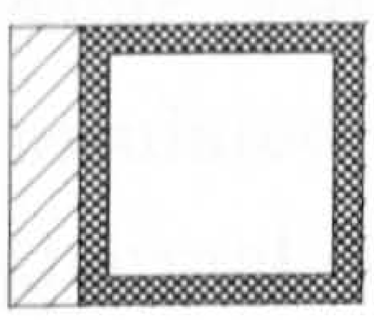


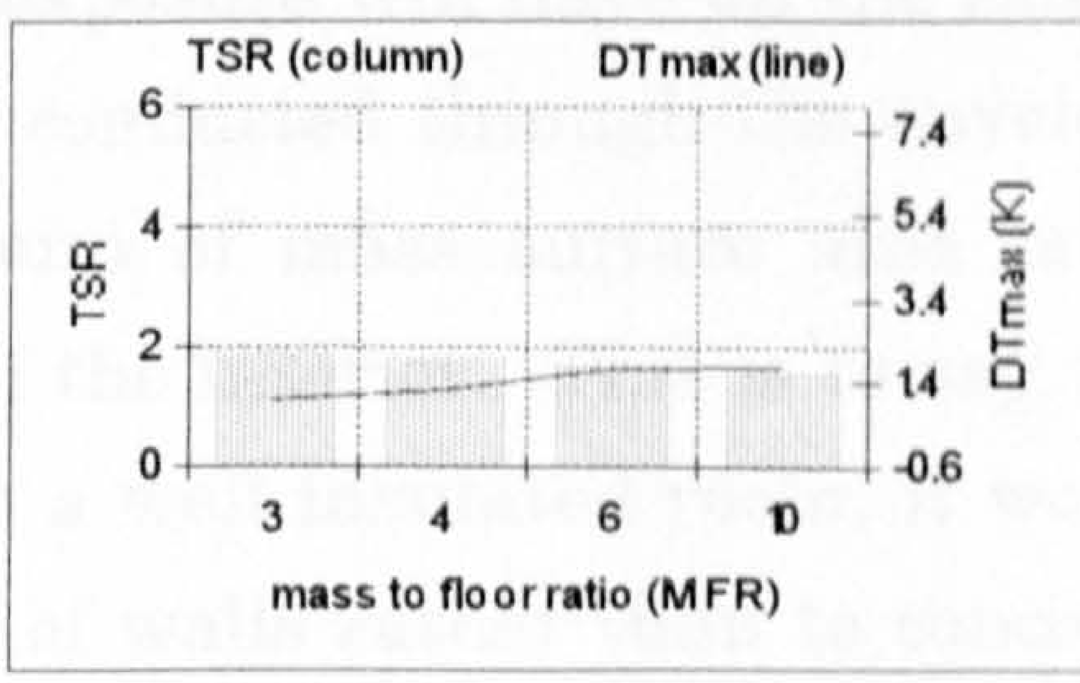
increasing MFR improves *TSR* and *DTmax*



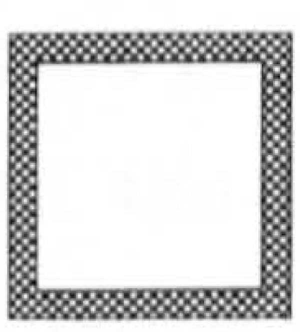


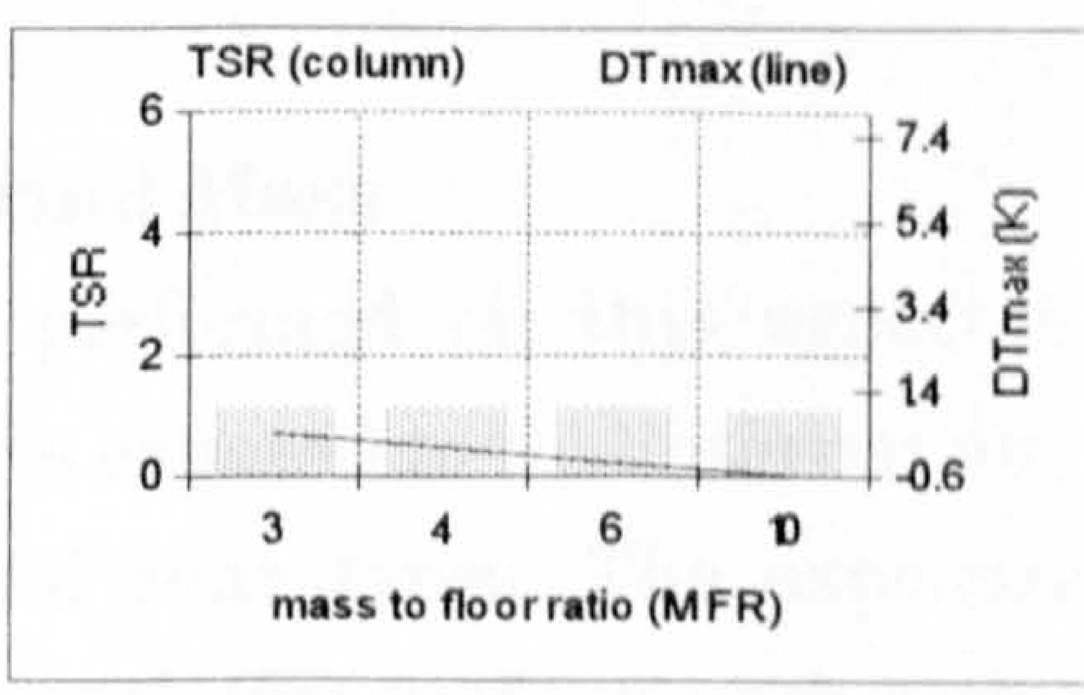
improves *TSR* and *DTmax* if st is 0.15 m or thicker





MFR makes little effect on *TSR* and *DTmax*





increase *MFR* reduces both *TSR* and *DTmax*

6.6 Summary of Findings

The aim of this study was to identify relevant issues concerning the effect of thermal mass of a single enclosure with particular attention to the aspects of mass quantity and distribution and the ways in which these aspects influence the internal temperature of a room.

6.6.1 Effect of Thickness

The thickness of the envelope has a strong influence on the internal temperature of the interior especially if the structure is not insulated. The effect of increasing the thickness of the envelope is particularly noticeable in lightweight elements where the temperature swings and peak temperatures tend to decrease but this effect is gradually reduced as the envelope becomes heavier until it reaches a point beyond which further thickness is essentially ineffective. Additional thickness may even increase the internal swing. The optimum thickness is determined by the properties of the materials used and by the levels of external insulation.

6.6.2 Effect of Mass Exposure

The aspect of exposure of mass surface emerged as one of the key factors of the effect of thermal mass. The effect of mass surface exposure tends to vary according mainly to the internal gains, and/or whether the space is night-ventilated or not. The conditions of the envelope (exposed or insulated) strongly influence the effect that altering the surface exposure will have on the internal conditions of the room. If no solar heat gains are conducted through the envelope into the room i.e. this is well insulated, the exposure of mass surface area prevails over thickness to improve thermal conditions of the interior. This is to say that if additional thermal mass is to be introduced into a well insulated room, it would be more effective to spread it throughout the area of walls rather than to concentrate it on their thickness. Most cases indicated that the increase of mass exposure help improve thermal conditions by reducing internal swings and peak internal temperatures.

6.6.4 Effect of Internal Mass

All the simulations performed on this aspect indicated that the introduction of internal mass which is exposed to the internal air, will result in improvements of the internal climate of all zone types. The exposure of mass to the interior is more effective on elements with two surfaces such as internal partitions. If further surface area of internal mass is added to the space, it is better to do so by placing internal partitions or other internal elements with two faces exposed rather than increasing the area of envelope or inter-zone walls. This is particularly noticeable for rooms with exposed envelopes. The distribution of internal mass and thickness of internal partitions are also important considerations. Better thermal results were obtained with more partitions of optimum thickness (between 10 cm. and 15 cm. thick) than fewer but thicker partitions.

6.6.5 Effect of Mass Location

The tests performed on the sensitivity of location of thermal mass suggested that the floor is the location where the thermal mass has the lesser impact on the internal temperature. This observation suggests that most of the internal heat is deposited on the ceiling and walls due to heat distribution by forces of convection within the room. This correlates with observations in the measured buildings. For rooms exposed to the exterior on the four sides the position of mass on the roof results in lower swings and temperatures than on any other location. When only one of the walls is an external un-insulated element, the variation of thermal mass levels on this element has the greater effects on the thermal conditions of the room. As the structure becomes heavier the location of the thermal mass loses its importance.

6.7 Conclusions

The results of the parametric simulations suggest that in climate conditions with large temperature variations and frequent risk of overheating such as that of Seville, an optimum utilization of thermal mass can be a major design component within the strategies for achieving an efficient thermal performance of buildings. A judicious selection, distribution and design of thermal mass components can lead to improvements in the thermal conditions of buildings by minimizing peak temperatures and reducing internal swings. Avoiding large temperature swings inside buildings is directly associated with thermal comfort particularly in situations like in Seville where diurnal temperature variations can exceed 18 K.

The use of thermal insulation in the envelope of buildings in these conditions can further improve the internal climate of buildings by minimising solar gains through the opaque elements in periods of overheating and by reducing heat losses during cold days in winter. Thermal insulation is particularly beneficial in situations of considerable temperature difference between the inside and the outside. In conditions of smaller variations of external temperature, for example the case of Managua, the effect of thermal insulation will have a lesser impact on the temperature conditions. Thermal insulation may still help reducing solar gains through the building fabric since despite the smaller temperature differences between inside and outside, the solar radiation is usually high. However, in this situation where the necessary rapid heat dissipation by ventilation is not always possible, it would be more effective to minimise the influence of solar gains by the use reflective external surfaces and using an adequate element thickness.

The mass effects discussed in this section are based on simulations for a single enclosure in conditions of large external temperature swings for which weather data for Seville was used and the material selected for the building elements of the reference zone is concrete. The results shown for each mass variable, thickness, location and exposure would be less pronounced with materials of smaller thermal capacity and/or in conditions of less extreme temperature variations but the general tendencies would be similar. The extent of the effect of these other variables may be a case for further investigation.

7

Application of Diurnal Heat Capacity

7.1 Introduction

This chapter present a series of calculations based on the diurnal heat capacity method, ref. [5], [26], to estimate the internal temperature swings of a single enclosure for a number of thermal mass variables. The application of the procedure is discussed step by step, using a room with same characteristics of the reference zone adopted in the parametric studies, and the results compared with SERI-RES simulations.

7.2 Estimation of the *DHC* for the Reference Zone

The method consists of three general stages:

1) calculation of the *dhc* of each building element
2) calculation of the total *DHC* of the building
3) calculation of the internal temperature swing

The direct and indirect *dhc* types are calculated separately in the example and their use according to the type of thermal coupling of the surface is also discussed. The reference zone assumed for these estimates is made of a 0.20 m thick concrete envelope well insulated on the outside. The calculations and results for other materials and thicknesses are presented in Appendix A1.

7.2.1 Estimation of the *dhc* of elements

Using the thermal properties of the selected materials, the *dhc* of building elements can be calculated following procedure below:

a) estimate the admittance for a dimensionless element, (Y_∞)
b) calculate the *dhc* of the element with an infinite thickness, (dhc_∞)
c) calculate direct *dhc* of element, (*dhc (d)*)
d) introduce the effect of the surface resistance, (Rf)
e) calculate indirect *dhc* of element (*dhc (i)*)

The material used for the elements of the reference zone in this example is concrete with the following properties:

density	(ρ)	2100 kg/m^3
conductivity	(λ)	1.40 W/m K
specific heat	(c)	0.653 kJ/kg K

a) estimate the admittance for a dimensionless concrete element

From equation (3), where Y = admittance and P = 24h:

$$Y_\infty \quad = \sqrt{2\pi\ \lambda\rho c/P} \quad = 11.7\ \mathrm{W/m^2\ K}$$

b) calculate the dhc of the element with an infinite thickness

The *dhc* for an infinite wall is given by:

$$dhc_\infty \quad = \sqrt{\lambda\rho c P/2\pi} \quad = 44.85\ \mathrm{W/m^2\ K}$$

c) calculate direct dhc of element dhc (d)

The direct *dhc* of an element is the product of the magnitude corresponding to its penetration depth (ξ) and the *dhc* of an infinite wall (dhc_∞).

Using equation (11),

$$\xi = x / \sqrt{\lambda P/\pi\rho c} \qquad = x / 0.16$$

where x = the net thickness of the element.

Then for a concrete element with a 0.20 m thickness, the direct *dhc* is:

ξ = 0.20 /0.16 = 1.21
mag = 1.14 (from table A10.1, see appendix 10)
phase = 52° (from table A10.1)
direct $dhc = dhc_\infty$ * mag = 44.8 * 1.14
dhc (d) = **51.1 W/m² K**

e) introduce the effect of the surface resistance

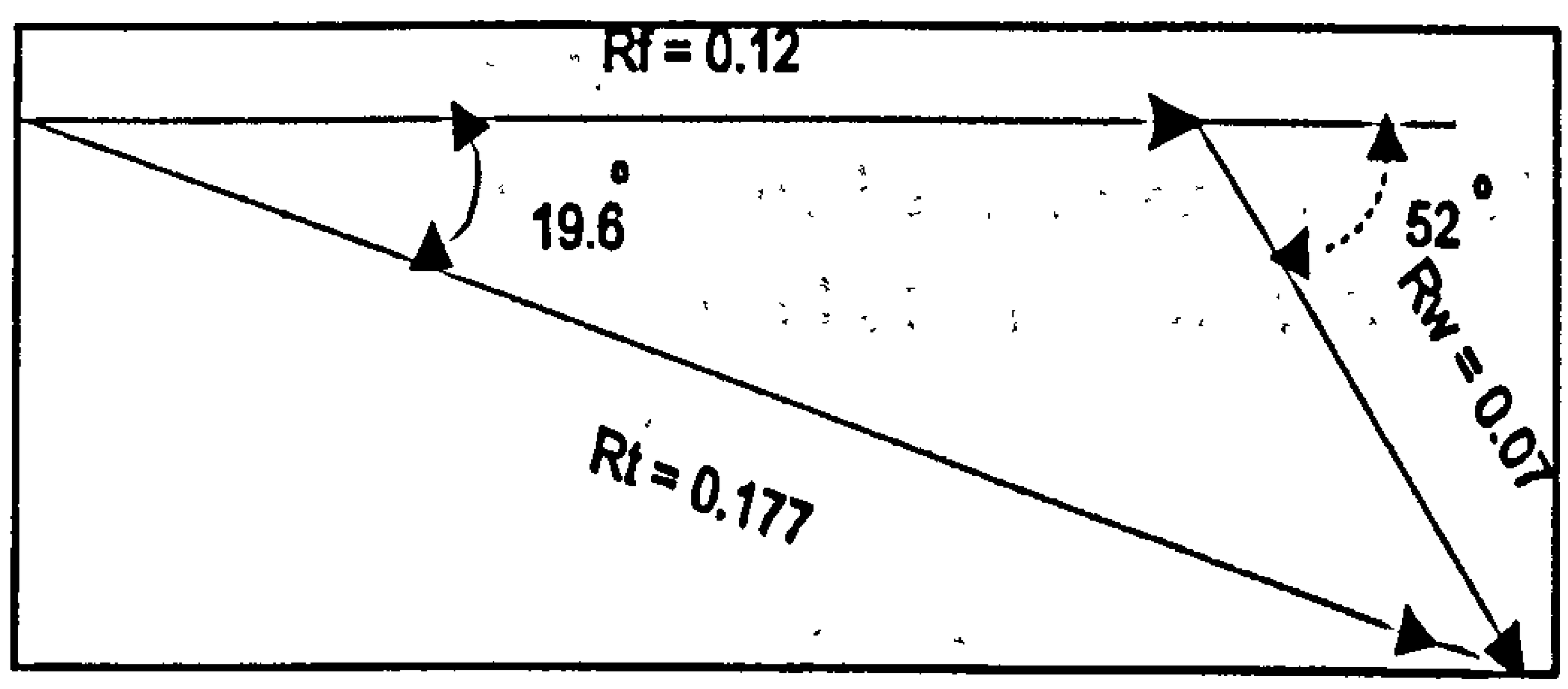
As discussed in section 2.4.6, the effect of the surface resistance should be accounted for in situations of convective coupling where the *dhc* of an element will be reduced by the effect of the air film near the surface. A value of 8.278 W/m² K was used for surface conductance of the air film (from SERI-RES default value for combined radiative and convective heat transfer coefficient for internal surfaces). Its reciprocal corresponds to a surface resistance of 0.12 m² K/W.

The admittance of an element of a defined thickness, (Yw) is the product of the admittance of a dimensionless thickness element and the corresponding magnitude, $Yw = Y_{\infty}$ (mag) ; then for a 0.20 m concrete element:

$Yw = 11.7 * 1.14 = 13.2$ W/m^2 K.

The thermal resistance of the element is the reciprocal of its admittance, $Rw = 1/Yw$, then, $Rw = 1/13.2 = 0.07$ m^2 K/W, with a phase lag of 52° (from table A10) which converted to time this is: 52/360 * 24 = 3.46 hrs. = 3 hours 35 min.

The addition of the resistance of the infinite wall and the resistance of the air film gives the total resistance of the element. This can be obtained graphically with the vector sum of the two resistances as shown in 7.1.



7.1 Vector sum of the resistance of the air film plus the resistance of the wall for a 0.20 m concrete structure shown as the diagonal vector.

The vector sum of the resistances of the infinite wall and the air film gives a total resistance 0.177 m^2 K/W with a phase lag of 19.6° (1 hour, 18 min.) The reciprocal of this value gives the total admittance of the wall. The results of the admittance of the wall with the effect of the surface resistance can be summarised as follows:

wall admittance	: $Yw = Y_{\infty} * (mag) = 11.7 * 1.14 = 13.2$ W/m^2 K
wall resistance	: $Rw = 1/Yw = 1/13.2 = 0.07$ m^2 K/W
air film resistance	: $Rf = 1/Yf = 1/8.278 = 0.12$ m^2 K/W
phase lag	: 52° (3 hours 35 min.).
series resistance	: 0.177 m^2 K/W

$Y = 1/0.177 = 5.62$ Wm^2 K

f) calculate indirect dhc of element dhc (i)

The indirect diurnal heat capacity is given by:

$$dhc\ (i) = (P/2\pi)\ (2\Delta\Phi/\Delta Ti)$$

where : Φ = the heat flux into the wall
ΔTi = the temperature swing of the room.

The thermal admittance in series estimated above is the ratio ($2\Delta\Phi/\Delta Ti$), then,

$dhc\ (i) = (P/2\pi)\ Y$
$dhc\ (i) = 3.82 * 5.62$
$dhc\ (i) = 21.5\ W/m^2\ K$

7.2.2 Estimation of Total *DHC*

The *DHC* of an element, *DHC*w can be obtained by multiplying the *dhc* of the component by its surface area. The addition of the *DHC*w of all elements gives the total *DHC* of the room or building.

$DHC_w = dhc_w * A_w$ and, $DHC = \Sigma\ DHC_w$

The total *DHC* of the reference zone was estimated for both direct and indirect *dhc* types. In order to increase the number of variables within the same enclosure, the total mass surface area of the reference zone was varied by altering the area of the window. The *dhc* of each element and the total *DHC* of the reference zone with a 0.20 m concrete structure is shown in table 7.1. See the *dhc* for other variants of the reference zone in Appendix 2.

Table 7.1
Total *DHC* for Reference Zone - Concrete 0.20 m

Surface	*Area* m^2	*dhc* W/m^2K		*DHC* kW/K	
		direct	*indirect*	*direct*	*indirect*
floor	64	51.1	21.5	3.27	1.37
walls	98	51.1	21.5	5.01	2.11
ceiling	64	51.1	21.5	3.27	1.37
window	30	-	-	-	-
total	226	-	-	11.55	4.85

The total *DHC* values shown above correspond to a single enclosure where all the surfaces have the same thermal coupling type, i.e. the direct *dhc* can be used for the cool period when solar gains are allowed through the south glazing and the indirect is used for the warm period. When the internal layout of a building includes more than one space, the thermal coupling between surfaces and the internal air may not always be the same and a more detailed classification should be used. A diagram for the subdivision of spaces of the building can facilitate this classification, (see example building in chapter 8). The classification of *dhc* type for each surface on each space can be made according to the following the criteria:

Table 7.2
***dhc* Type According to Surface Condition**

Location	*dhc* Type
The surface of any massive material that receives direct sun	direct with enhancement factor
Covered floor (or any covered surface)	isolated
Walls that enclose a room with solar gains	direct
Ceilings that communicate by convection with rooms with solar gains	direct
Walls that communicate by convection with rooms with solar gains	indirect
Uncovered floor in rooms with solar gains (not sun-lit)	indirect
All surfaces of rooms with internal gains only	indirect
All surfaces in closed-off rooms	isolated

Exceptions are: floors in rooms with internal gains only, because of their poor convective coupling with the room air these are defined as isolated ($dhc = 0$). All ceilings due to their good heat exchange with room air are classified direct provided there is a good convective connection. Based on the above criteria, a classification of the surfaces can be made for each space.

The *dhc* of surfaces which are directly sunlit will be increased by an enhancement factor. This can be obtained by roughly estimating the fraction of the solar day that the surface is sunlit, f, and the absorptance of the surface, α. The relation is: $dhc\ (d) * (1 + \alpha f)$. This factor obviously is only used in calculations for the cool period where some of the internal surfaces will have a portion exposed directly to solar radiation. Finally, to account for the *dhc* of the furniture, in lieu of other data, a *DHC* value of 1.06 W/K can be used for each square meter of floor area for normal furnishings.

The next step is to estimate the total heat exchanging area of the internal surfaces. The total area of internal surfaces may have to be reduced by a factor that accounts for objects such as chairs and tables pushed against the walls, and pictures, file cabinets and other pieces of furniture which may interfere with the heat exchange. Having determined all *dhc* values and the area of the surfaces, the total *DHC* of the building can then be estimated with the addition of the (*dhc* . A) values of all surfaces.

7.3 Estimation of Internal Temperature Swing

The general expression for the calculation of the internal temperature swing is,

$$\Delta Ti\ (swing) = \frac{\Phi s - (Ti - To)\ hlc/2 + \Phi i/2}{DHC} \qquad (13)$$

where:
Φs = daily solar gains
Ti = daily average internal temperature
To = daily average outdoor temperature
hlc = heat loss coefficient
Φi = daily internal gains

For a building with no auxiliary heating this can be simplified as:

$$\Delta Ti = 0.61\ \Phi t\ /\ DHC \qquad (16)$$

where Φt is the total heat gain.

In overheating conditions direct solar gains can be reduced by shading but internal gains plus gains due to diffuse radiation, gains through the opaque surfaces, and gains by ventilation may have to be included. In order to simplify the calculations for the reference zone used here, only two cases were considered: solar gains for cool period calculations and internal gains for the warm period. The solar gains were obtained from equation, (23):

$\Phi s = I \times A$ where,
Φs = solar gains
I = daily incident solar radiation
A = window area

Using solar radiation data for Seville, the internal temperature swing of the reference zone can be estimated as follows:

I = 3.28 kWh/m^2 day

A = 30 m^2

Φs = 3.28 * 30 = 9.84 kWh

then using equation (14),

$\Delta Ti = 0.61 * 98.4 / 11.55$

$\Delta Ti = 5.2$ K

7.3.1 Comparison Between DHC and SERI-RES Results

Swing calculations for the reference zone with different window areas and the comparison with SERI-RES predictions are shown in table 7.3 and graphical results included in table 7.4. For the sake of comparison, the heat gain rates used in the *dhc* procedure were also used for the SERI-RES simulations. The material properties and surface coefficients values were also set equal in the two models. According to the type of thermal coupling, the direct *dhc* value was used for the cases where solar gains were included (cool period) and the indirect *dhc* for the warm period calculations. For results of calculations including different thicknesses, other materials and various window areas see Appendix A3.

Table 7.3

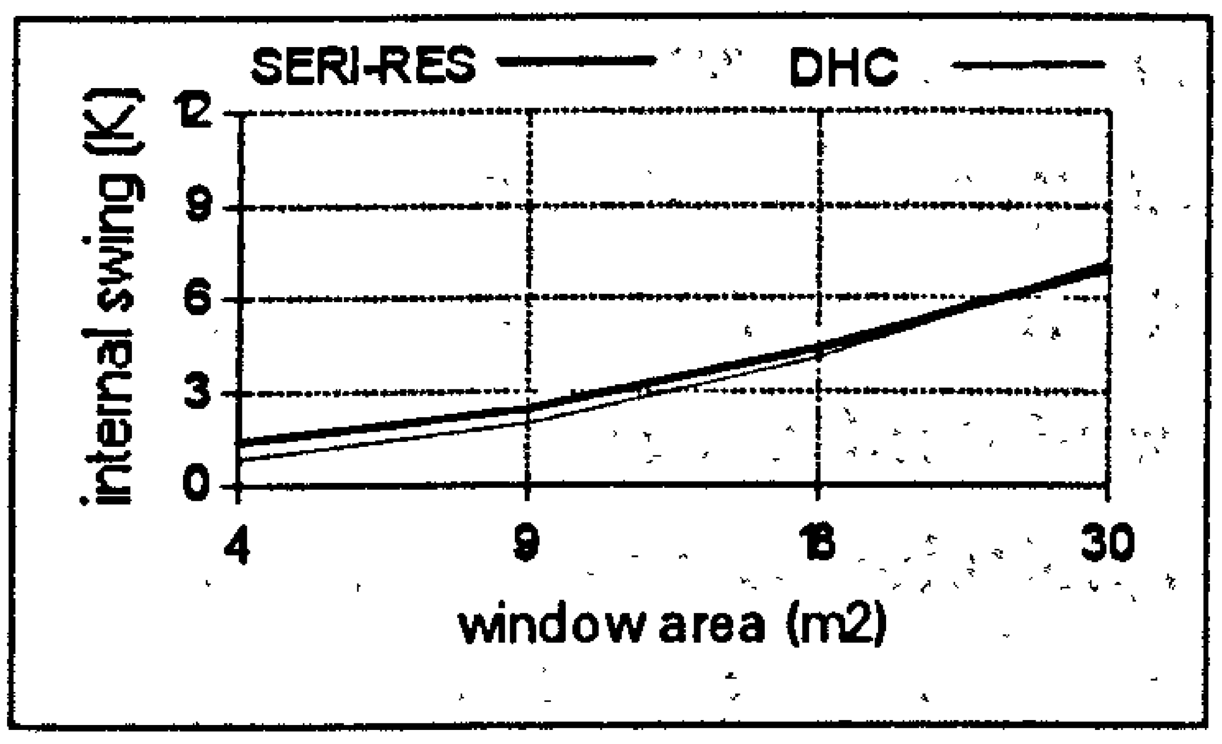
Predicted Internal Temperature Swing Reference Zone Types 1 - 5. Concrete 0.20 m

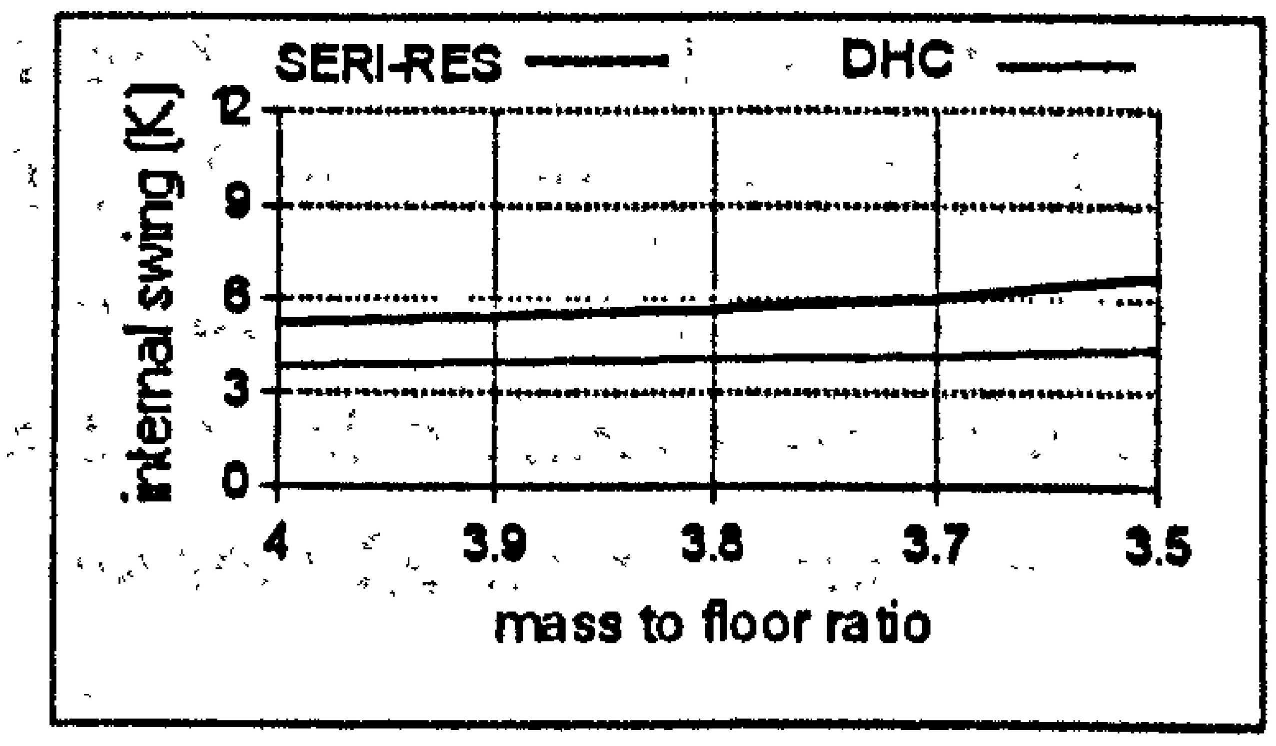
Zone Data			*Cool Period*		*Warm Period*	
Zone Type	*Window Area m^2*	*Mass / Floor Ratio*	*Swing DHC K*	*Swing SERI K*	*Swing DHC K*	*Swing SERI K*
1	0	4.0	-	-	4.0	4.4
2	4	3.9	0.6	1.21	4.1	4.6
3	9	3.8	1.4	2.1	4.2	4.9
4	18	3.7	2.9	3.7	4.3	5.2
5	30	3.5	5.2	5.9	4.5	6.0

Table 7.4 Internal Temperature Swing Predictions from *dhc* and SERI-RES

Envelope	*cool period*	*warm period*

C = 0.10





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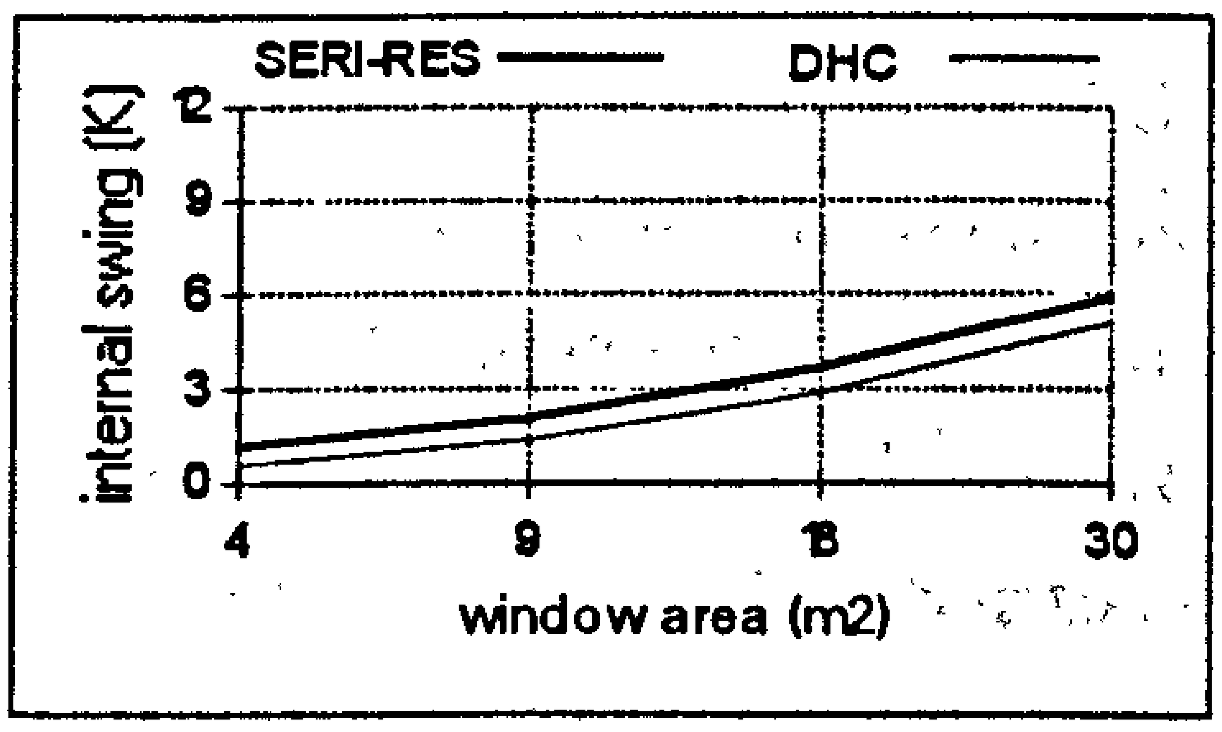
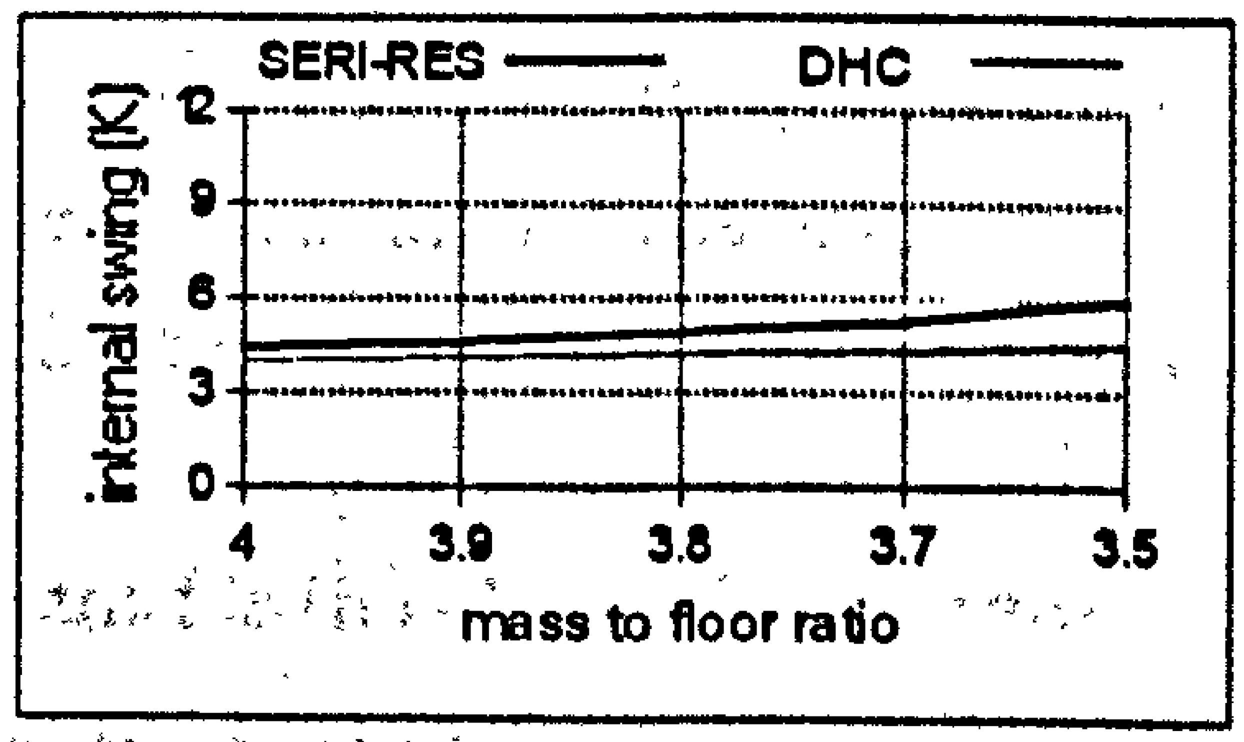
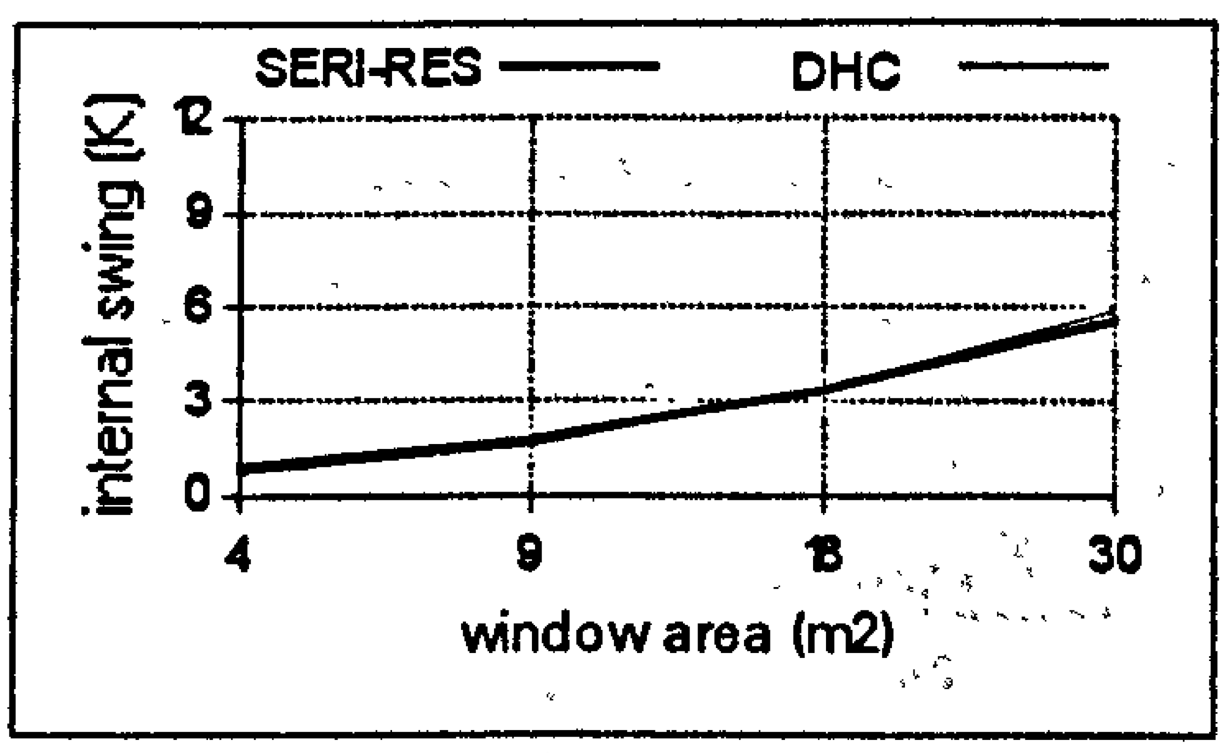
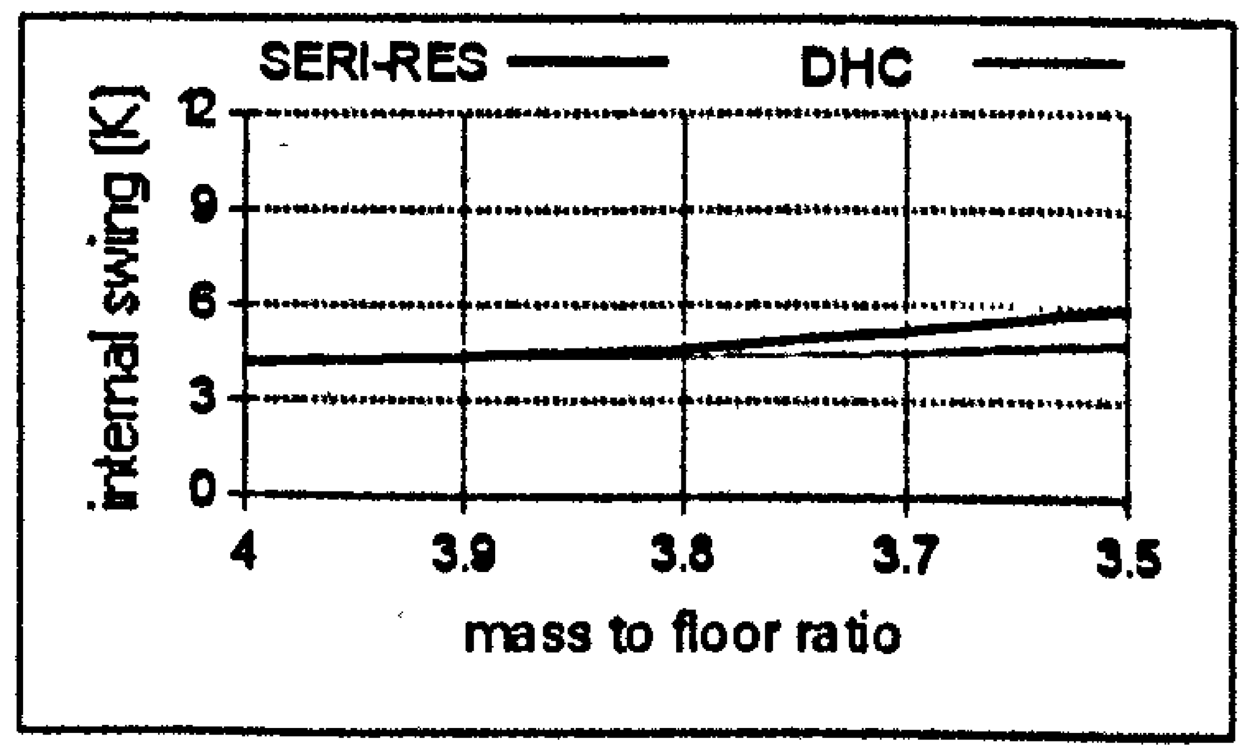


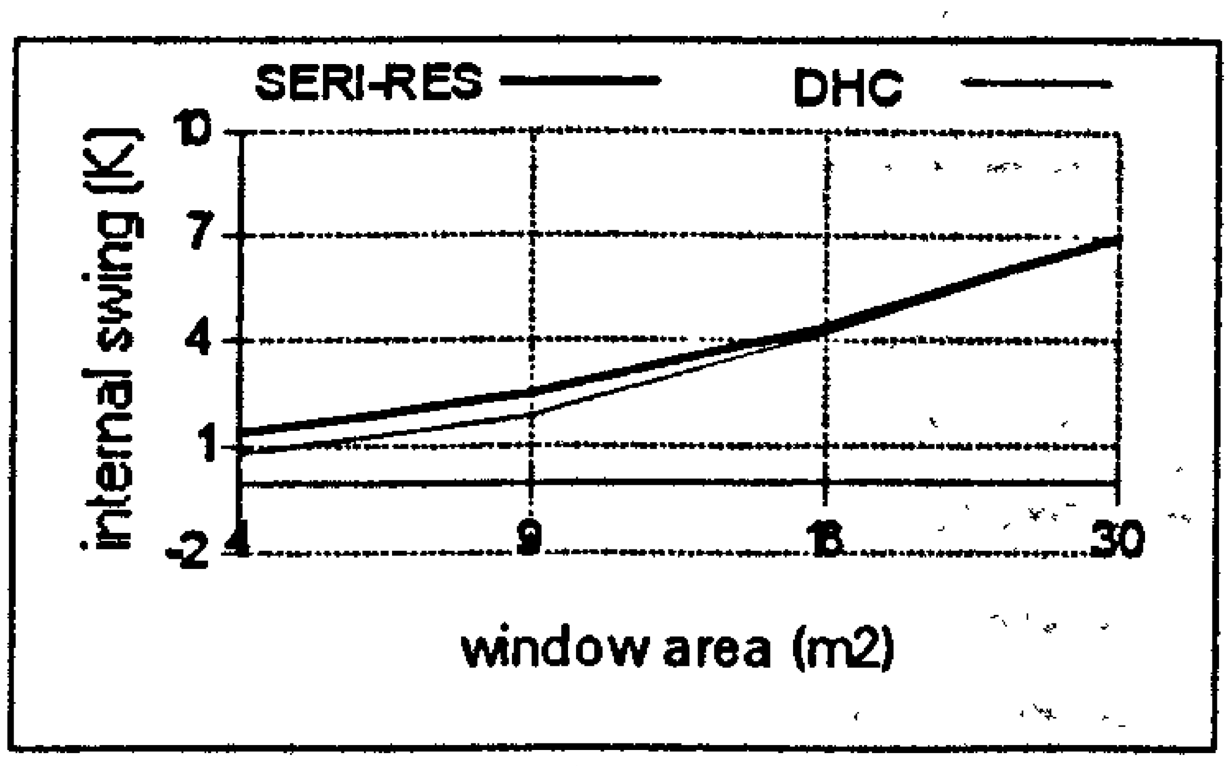


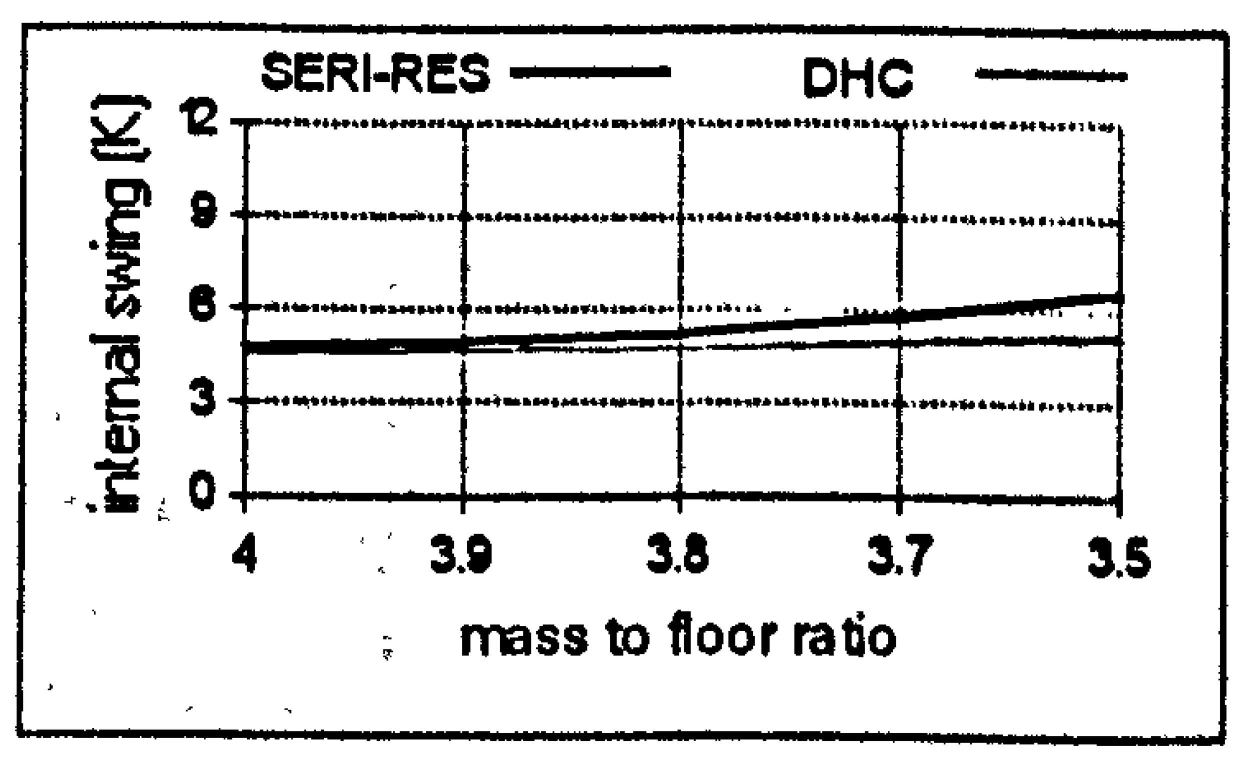
C = 0.40



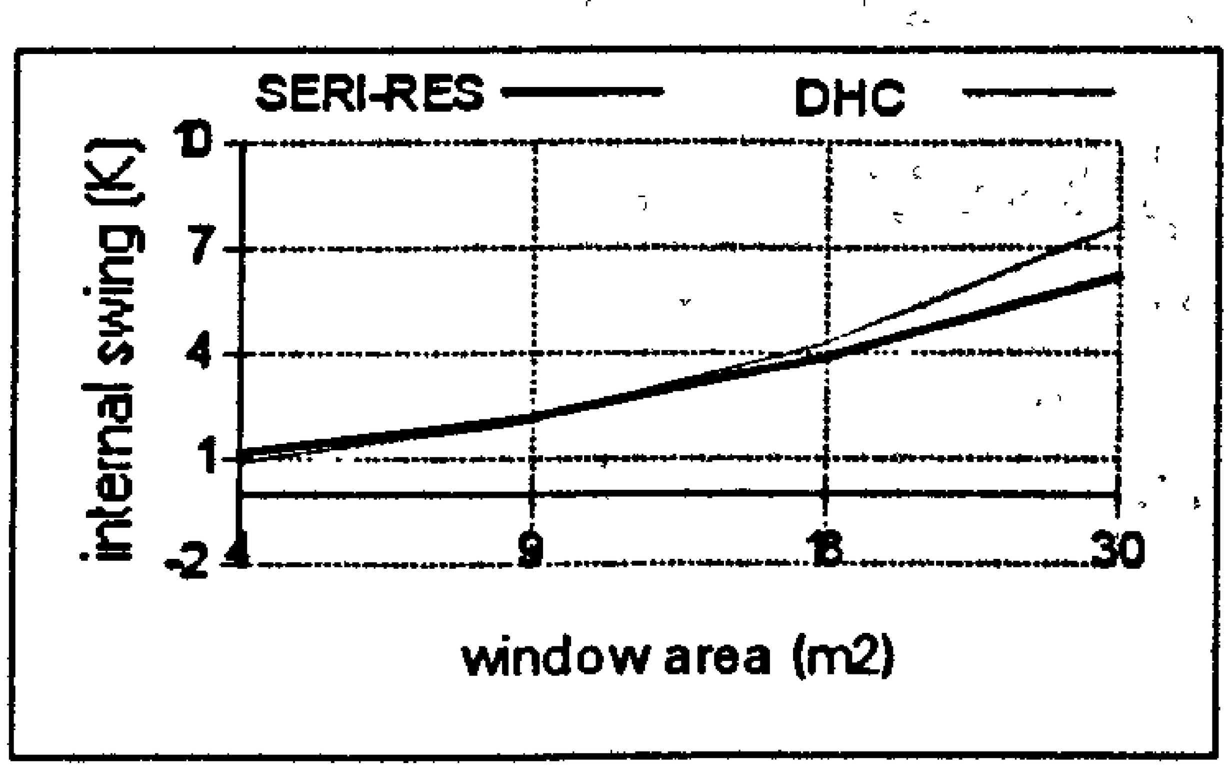


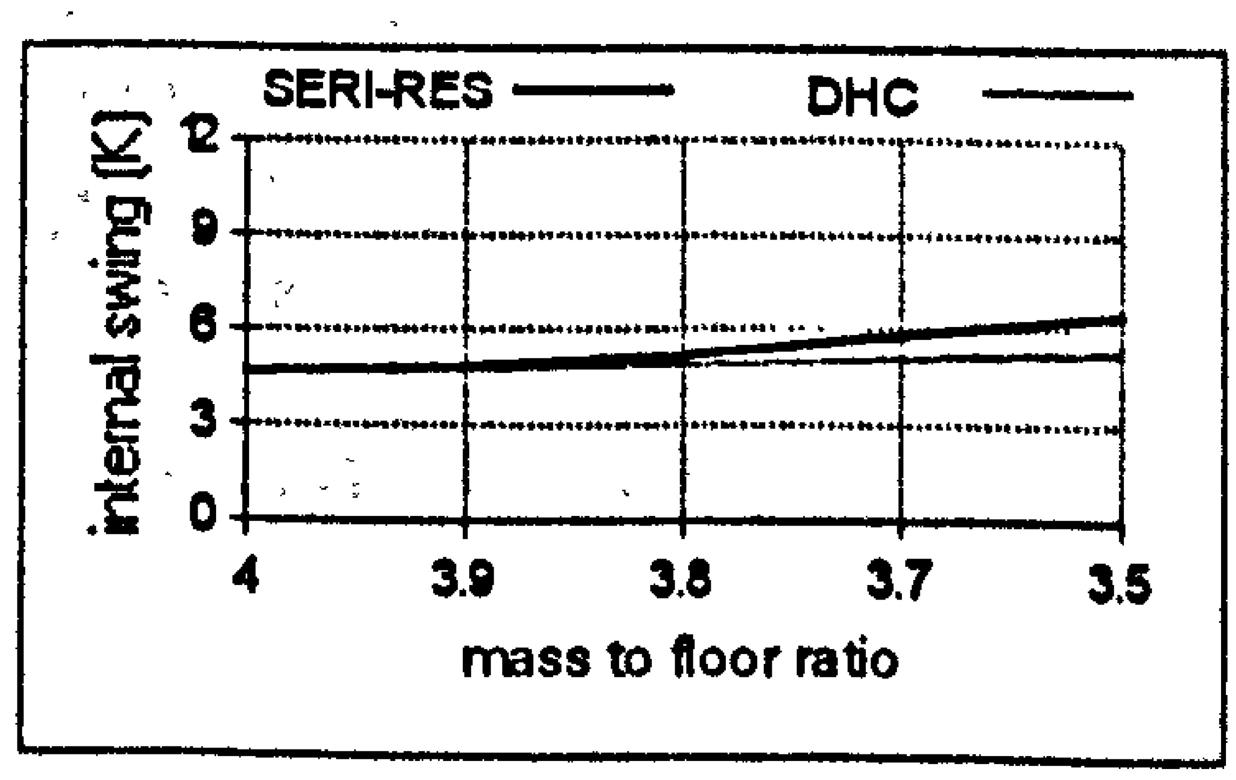
B = 0.20





B = 0.40





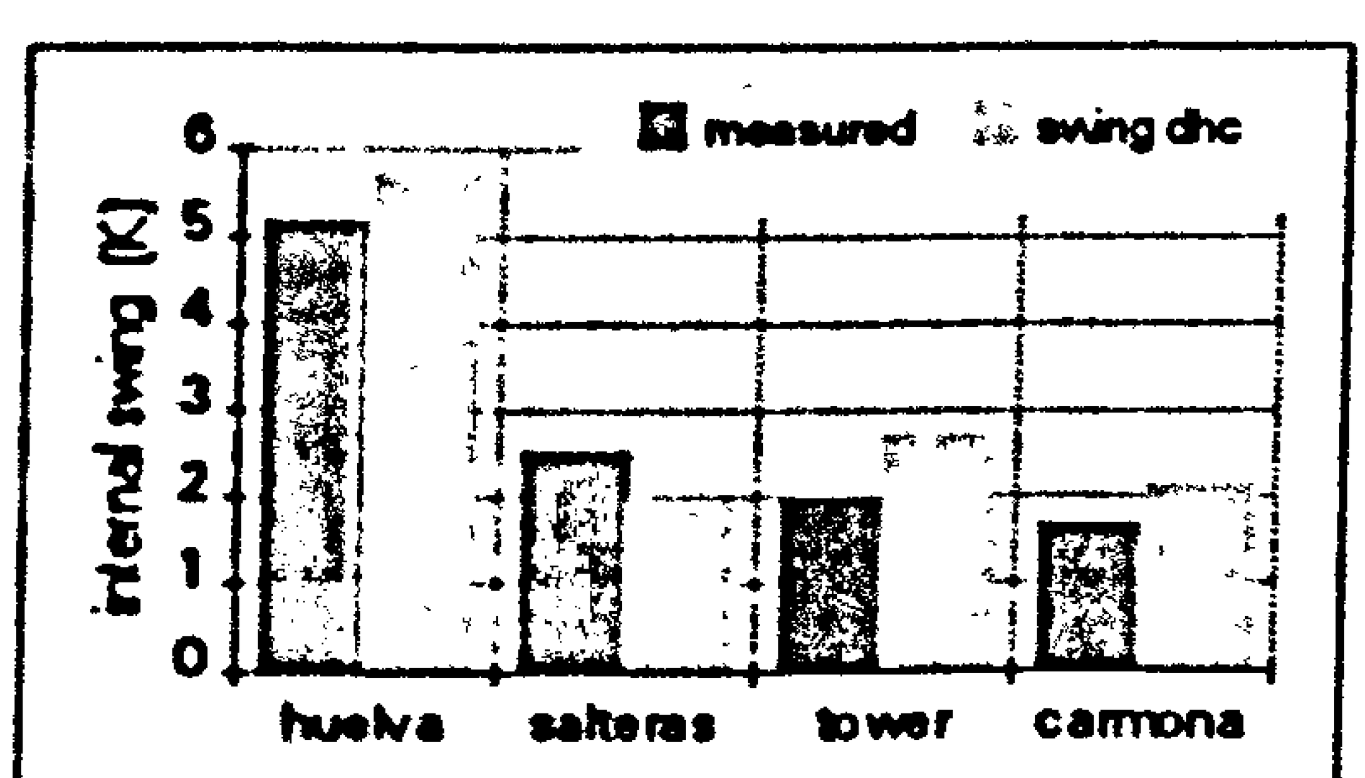
7.4 Diurnal Heat Capacity of Measured Buildings

The calculation of diurnal heat capacities for composite materials such as hollow concrete or hollow brick blocks is a complex process due to the resultant geometry of the different constructional units. Tables A3.1 and A3.2 provide *dhc* values for various materials and concrete masonry units. These were used for the *dhc* calculations for some of the elements of the monitored buildings. Because the prevailing thermal condition in the buildings is that solar gains were absent, the indirect *dhc* type was used. The calculation of the *dhc* for each of the case study buildings is shown in Appendix A4.

For the monitored buildings, the total heat gain value included the gains through the fabric plus the internal gains. These calculations were carried out using the total heat loss coefficient of the envelope and the temperature difference between outside and the inside. For the day hours, the external temperature was increased using the concept of sol-air temperature in order to account for the effect of solar radiation. The heat gain calculation of each building is presented in Appendix A4.

Table 7.5
Measured and Estimated Internal Swings based on the *dhc* Method.

building	*internal swings K*	
	measured	*swing dhc*
Huelva	5.2	5.7
Salteras	2.5	1.9
Tower	2.0	2.7
Carmona	1.6	2.1



7.2 Measured and Estimated Internal Swings with the *dhc* method.

7.5 Conclusions

The temperature swing results based on the diurnal heat capacity procedure showed fairly good correlation with both, the thermal simulations with SERI-RES and with measured data. Considering the degree of uncertainty with regard to the exact *dhc* values for the multi-layered walls, the internal swing predictions of the real buildings are very close. With the reference zones, where the simpler structures used facilitated the calculations, the approximation is even greater.

In addition to the agreement observed on the temperature swing results, the *dhc* method correlates with the findings of the simulations in various ways. In the aspect of element thickness, the *dhc* method suggests an optimum thickness, given by the definition of the dimensionless thickness of the element expressed in equation (12) in section 3.3. In the case of the concrete insulated zone type, the optimum thickness calculated with the *dhc* is very close to the limit thickness where the *TSR* curve begins to show smaller effects, see graph 6.2.

The aspect of mass exposure is also a point of agreement between *dhc* and SERI-RES calculations. For a uniform day-time heat gain regime inside a well insulated enclosure, the increase of mass surface area improves performance by decreasing the internal temperature swing. The point on mass distribution is also an accordance since the *dhc* calculations indicated that the mass dispersion throughout the room (for example in the form of internal partitions and other exposed elements with both surfaces facing the room) is more effective than concentration in individual elements.

The *dhc* method can be used as a design parameter for the prediction of internal temperature swings both for cool and warm periods if the properties of the materials to be used are known and reliable solar radiation data can be obtained. For the purpose of warm period calculations, in which no direct solar gains should be accounted for, a well defined schedule of internal gains is necessary. The application of the *dhc* procedure for a whole building is presented in the next chapter.

8 Design Guidelines

8.1 Introduction

This chapter discusses a series of design measures aimed at the improvement of the thermal performance of non-domestic buildings in locations with overheating as the main thermal problem. The recommendations focus particularly on the optimisation of the inertia effects of the building mass in order to reduce internal temperature swings. The concept of diurnal heat capacity discussed in chapter 7 is used here where the application of the method is illustrated with an example building and the results presented in a calculation worksheet designed to simplify the procedure. In addition, a series of qualitative guidelines in relation to mass optimisation are also given.

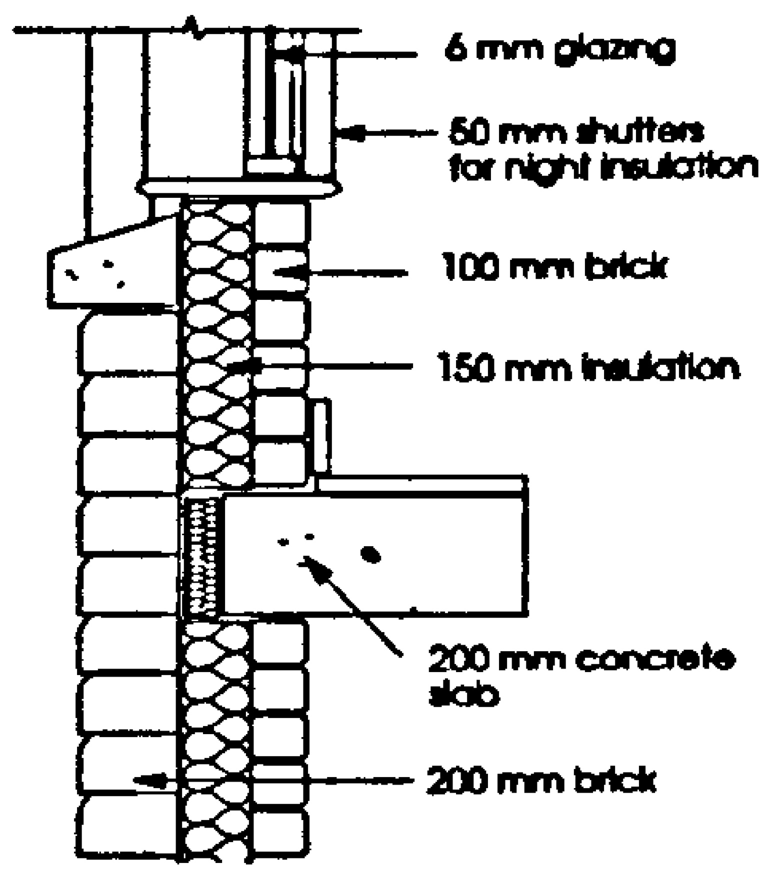
8.2 The Example Building

Using Seville as the selected location, the example building was defined as a two story, open plan office with a total floor area of 436 m^2, (see building description in 8.1). The materials assumed for the building elements are brick for walls and partitions, and concrete for floors and ceilings. A number of thermal mass variations were performed by replacing the materials and dimensions of the building components. Other variants include adobe walls, brick floors and wooden ceilings. In all variants, the envelope of the building is assumed to be well insulated on the outside with an insulation layer of 150 mm (see wall section) and the windows are designed to provide effective shading during the summer months and good solar access through south facing glazing during the cool period. Solar gains for the cool period are ensured by the large south facing clerestory windows along the east west axis of the building.

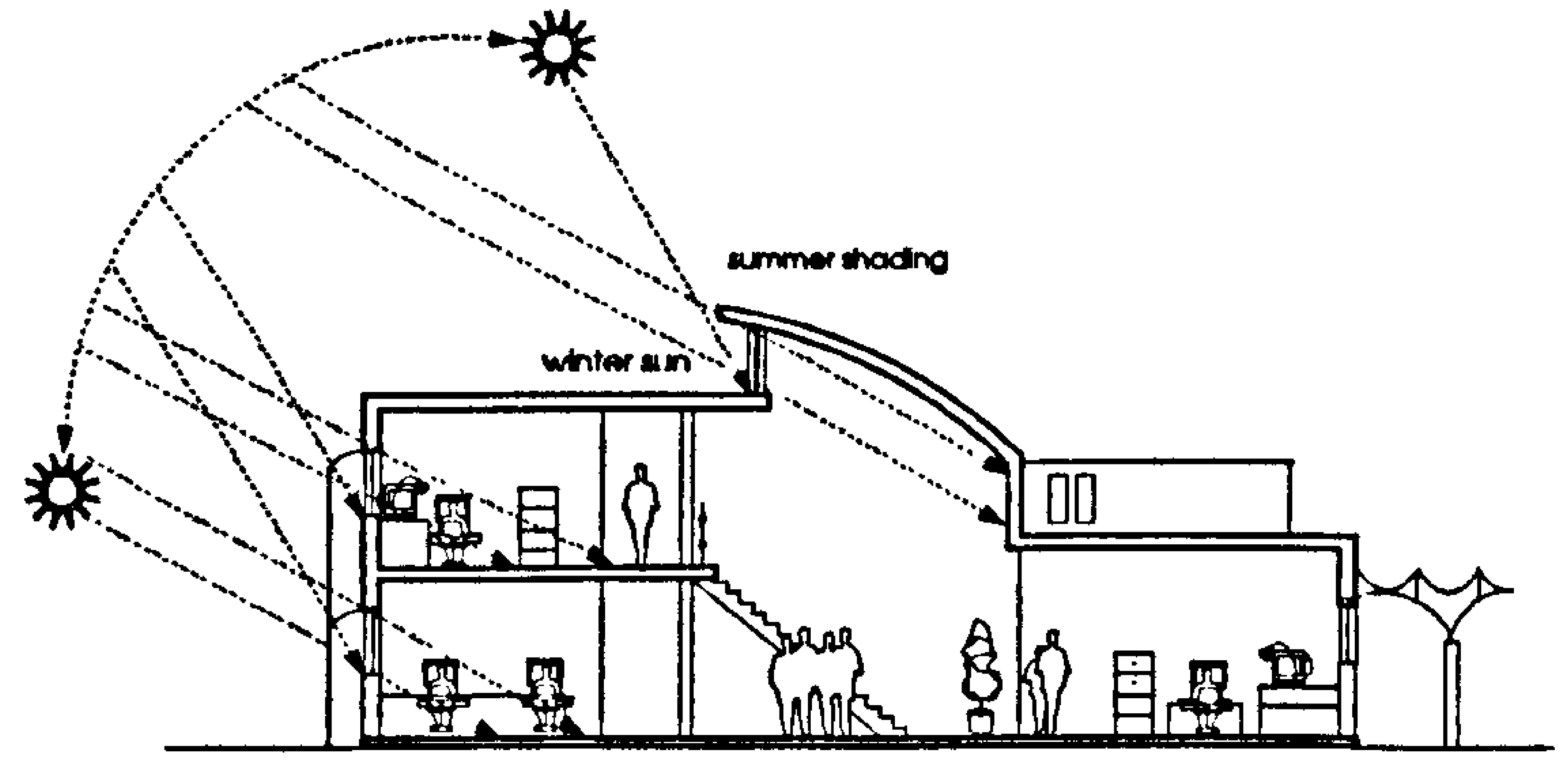
8.2.1 Estimating the *DHC* of the Building

To estimate the *DHC* value of the elements of the building it is necessary first to assign the *dhc* type according to the thermal coupling of each surface. This process can be simplified by subdividing the building into individual internal spaces so that the surfaces can be classified separately for each space, (see space classification diagram in 8.1). The *dhc* of each surface can be estimated following the procedure given in section 7.2. The *dhc* for various materials and thicknesses have been calculated and the results are included in the library table of the worksheet in section 8.3. The selection of *dhc* values for each surface on each space can be made according to the thermal coupling criteria discussed in chapter 7 (see table 7.2). In this building, space 2 (reception) and space 7 (toilets, storage and meeting rooms) are assumed to be with the doors closed. Because their little participation in the thermal exchanges occurring in the main office areas, these spaces were classified as isolated.

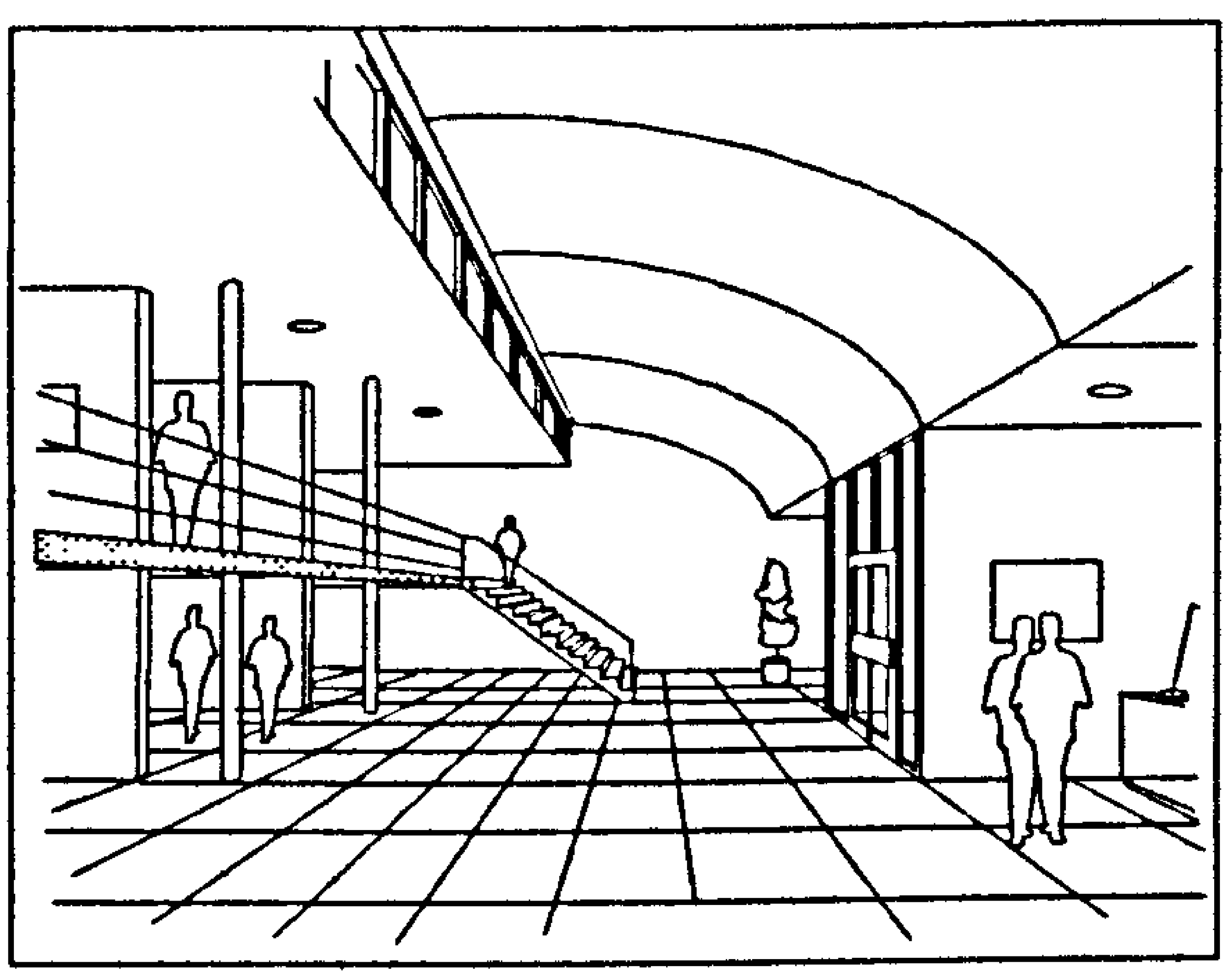
Example Building



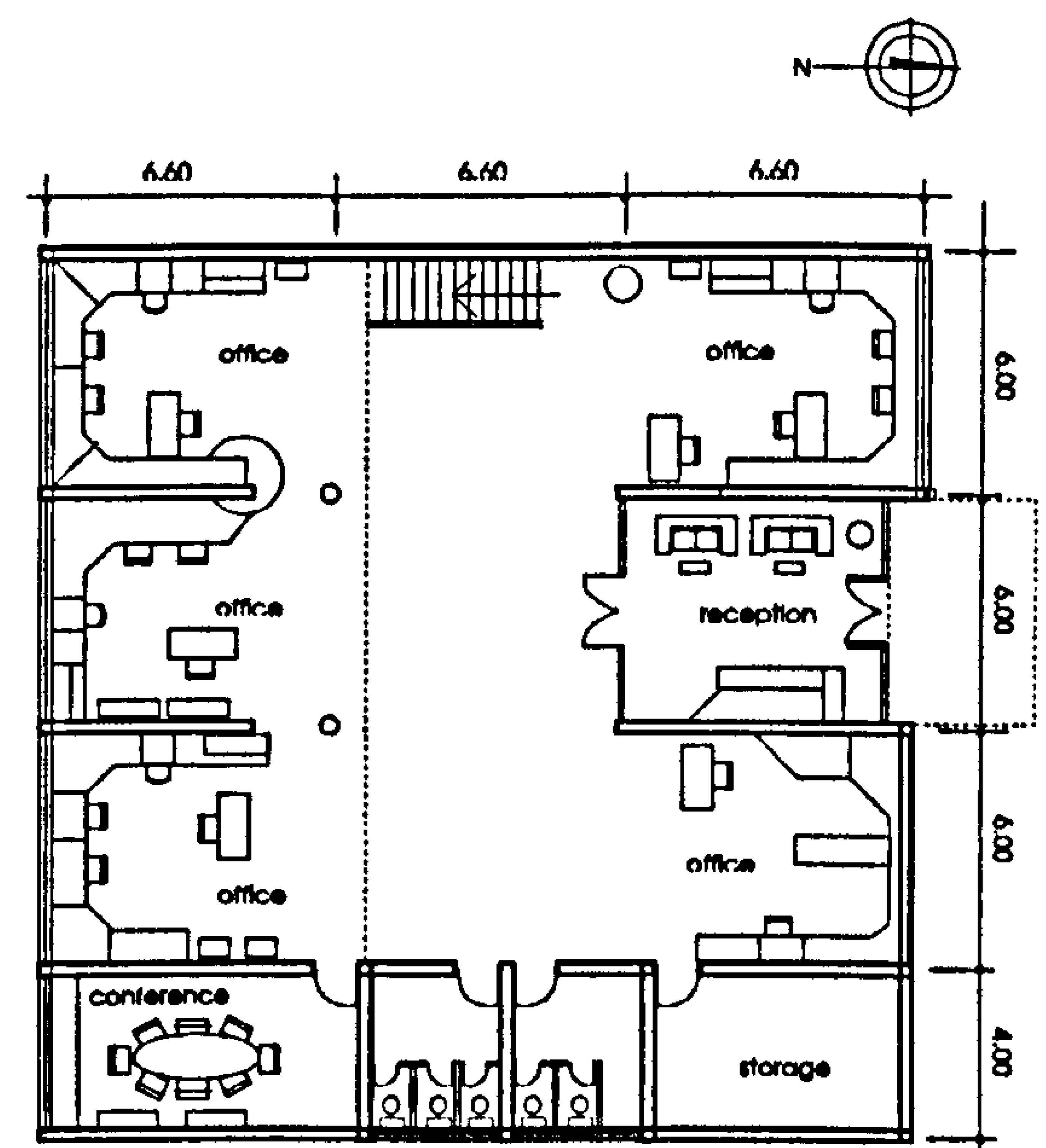
wall section



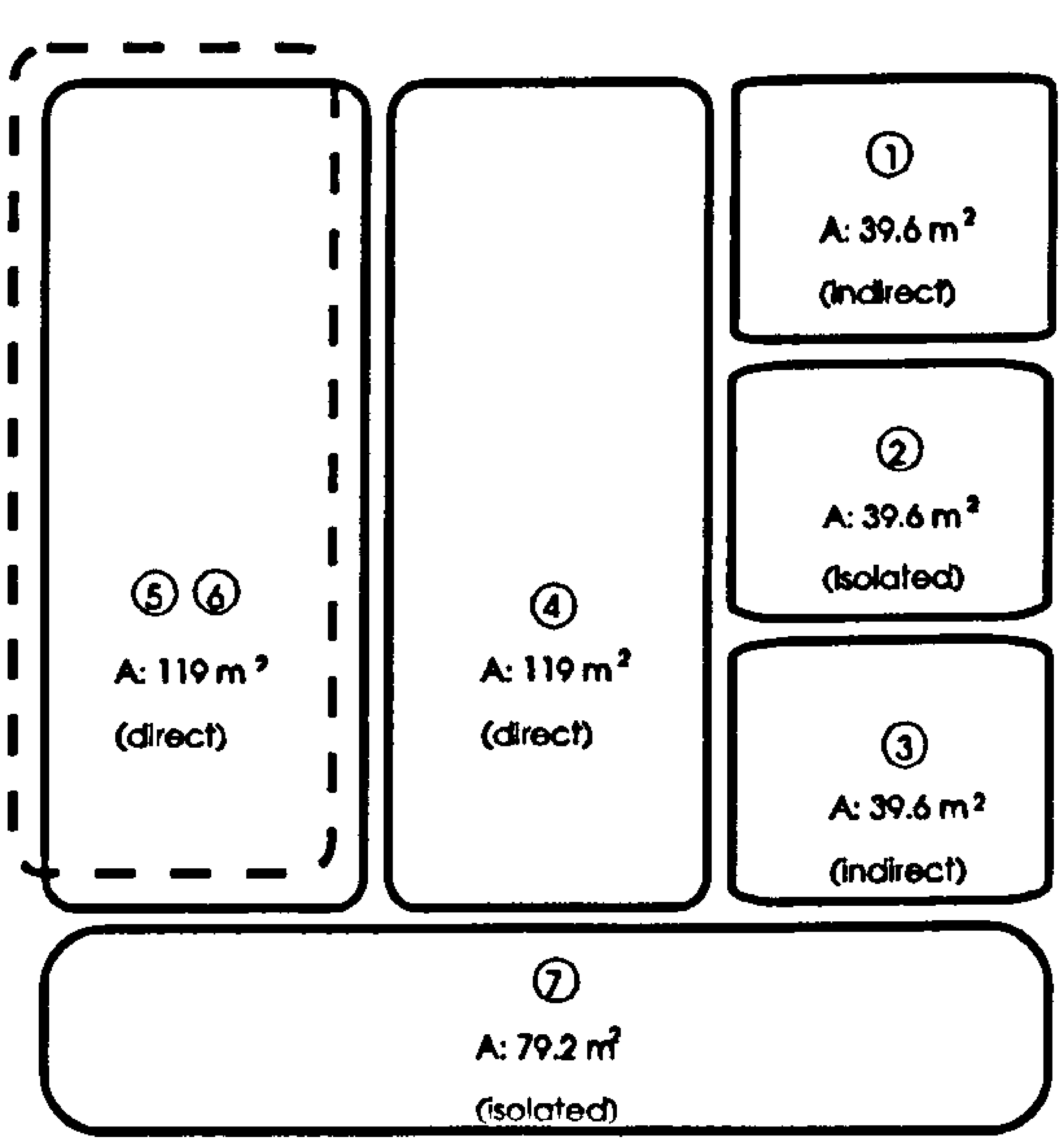
north-south section



internal view



ground floor plan



internal space diagram

Building Data

Floor Area:	436 m^2
Volume:	1372 m^3
Window Area:	84 m^2
Mass to Floor Ratio:	3.4
Heat Loss Rate:	1149 W/K
HLR / Floor Area:	2.6 W/K.m^2 (1ac/h)

8.1 **Plan, section and internal view of the office building example. The lower diagram shows the internal space subdivision of the building indicating the size and classification of each space.**

Having defined the area and *dhc* of all the surfaces that will be thermally active in each space, the *DHC* of each element and the total *DHC* of the building can be calculated.

Finally, with the total *DHC* and the total daily heat gains of the building, the internal temperature swing can be estimated using equation (16), (see chapter 7). The swing predicted to this point is due to the effect of the building mass and the heat gain with an assumed constant ventilation of 1 air changes per hour. A relation to determine the mean internal temperature can be made based on the average external temperature and the heat loss rate of the building. This relation is given by $Ti = To + \Phi t/hlc$. A proportional increase of the heat loss coefficient can be used to account the effect of night ventilation.

8.3 Calculation Worksheet

In order to facilitate the calculations of the example building a worksheet has been designed using a spreadsheet program to estimate the resultant temperature swings of the building according to its diurnal heat capacity and the total heat gains. The equations introduced into the worksheet are those of the *DHC* procedure described in chapter 7. The calculation worksheet is divided into two sections. Section 1 is concerned with the description of the building where the data regarding the area of the surfaces, the covered fractions and the *dhc* value according to surface type are introduced for each space of the building. In this section the total mass surface area and the *DHC* of each surface is calculated and with the sum of all *DHC* values the total *DHC* of the building is obtained. Section 2 allows the introduction of the heat gain data which in turn are used to estimate the daily totals accounting for solar gains through glazing and internal gains from occupants, lighting and equipment. The mean external temperature and the night ventilation rate can also be entered here. Once this information has been input, section 3 returns the resultant internal temperature swing. An estimated mean internal and peak temperatures are also shown here. A fourth part of the worksheet includes tables for *dhc* values of various materials and for the calculation of the enhancement factor used for sunlit portions. The values on these tables can be used for the introduction of data on section 1. The shaded areas show the values calculated by the spreadsheet.

8.3.1 Introducing Data for the Example Building

The data for the example building were introduced into the worksheet for estimates for the warm and cool periods. In order to compare the effect of different materials, the exercise was carried out using two versions of the same building where a different set of materials were selected for each version. The first version, *office-1* is made of adobe walls and wooden internal partitions. The ceilings are also with wood finish and the floors made of clay tiles. In the second version, *office 2*, the adobe and wood of the walls and partitions are replaced with exposed brick surfaces and the clay floor and wooden ceilings with dense concrete. The detailed description of the elements is included in each worksheet.

The general assumptions in these calculations are that in the cool period the building would allow solar penetration through south facing glazing and some of the surfaces will be directly exposed. This means that some surfaces will be given direct *dhc* values, some will have the enhancement factor and some will have and indirect *dhc* value. For the warm period the building will be perfectly shaded where the heat source will be produced by internal gains and by the effect of diffuse radiation. The surfaces in these conditions will therefore have an indirect *dhc* value. Based on these assumptions and assisted by the support tables, the *dhc* values were introduced following the criteria on table 7.2. Other assumptions are: The internal surfaces of elements with solid materials such as brick or concrete used in this building are not covered with plaster or other finishes in order to increase their *dhc*. The brick walls and partitions are painted light cream assuming an absorptance value of 0.4. For the second version, the ceilings are of exposed concrete painted white and the floors of polished light grey concrete tiles. These were given an absorptance factor of 0.6.

8.3.2 Heat Gains

The internal heat gain data used are normal values for typical office use with 7 W/m^2 for lighting and 7 W/m^2 for office equipment. These values can then be reduced assuming the use of more efficient lighting and electric appliances. In summer, artificial lighting can be replaced by daylighting for further reductions of the total heat gain. See daylighting levels of the example building in Appendix 9. Occupancy patterns were determined with a density of 14 m^2/person in office space.

The calculations were performed using solar radiation and temperature data for Seville in January for the cool period and in August for the warm period. The building information, heat gain data and the resultant temperature swings for each version of the example building are presented in the worksheets. To allow comparison, both versions were given the same internal heat gain characteristics, solar gains and temperature data. The difference shown responds solely to the effect of the building mass. A third worksheet shows the results of an improved *office 2* incorporating the effect night ventilation plus further reductions to the internal gains by eliminating artificial lighting. The building data of the example building was also introduced into SERI-RES with simulations results in good agreement with the values shown here. See SERI-RES results in Appendix 9.

Diurnal Heat Capacity Calculation Worksheet	**Building Name:**	Office 1
	Location:	Seville

1 Enter Building Mass Data

building information						DHC for summer		DHC for winter calculations			
space	building element	total area m2	subtract windows	covered fraction %	net area m2	dhc W/m2K	DHC kW/K	sunlit area m2	enhance factor	dhc W/m2K	DHC kW/K
1	floor	39.6	39.6	30	27.72	0.00	0.00	0.00	0.00	18.34	0.51
	walls	64.2	58.2	20	46.56	17.26	0.80	0.00	0.00	17.26	0.80
	partitions	0	0	20	0	0.00	0.00	0.00	0.00	0.00	0.00
	doors	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
	windows	6	0	0	6	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	39.6	39.6	0	39.6	11.81	0.47	0.00	0.00	11.81	0.47
3	floor	39.6	39.6	30	27.72	0.00	0.00	0.00	0.00	18.34	0.51
	walls	64.2	56.2	20	44.96	17.26	0.78	0.00	0.00	17.26	0.78
	partitions	0	0	20	0	0.00	0.00	0.00	0.00	0.00	0.00
	doors	2	2	0	2	10.05	0.02	0.00	0.00	10.05	0.02
	windows	6	0	0	6	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	39.6	39.6	0	39.6	11.81	0.47	0.00	0.00	11.81	0.47
4	floor	118.8	118.8	30	83.16	0.00	0.00	0.00	0.00	18.34	1.53
	walls	118.4	78.4	20	62.72	17.26	1.08	18.00	1.32	31.17	2.13
	partitions	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
	doors	4	4	0	4	10.05	0.04	0.00	0.00	11.81	0.05
	windows	36	0	0	36	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	135	135	0	135	11.81	1.59	0.00	0.00	11.81	1.59
5	floor	118.8	118.8	30	83.16	0.00	0.00	8.00	1.30	18.34	1.57
	walls	93.6	73.6	20	58.88	17.26	1.02	0.00	0.00	31.17	1.84
	partitions	60	60	30	42	10.33	0.43	0.00	0.00	13.74	0.58
	doors	2	2	0	2	10.05	0.02	0.00	0.00	11.81	0.02
	windows	18	0	0	18	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	118.8	118.8	0	118.8	11.81	1.40	0.00	0.00	11.81	1.40
6	floor	118.8	118.8	30	83.16	0.00	0.00	8.00	1.30	18.34	1.57
	walls	93.6	73.6	20	58.88	17.26	1.02	0.00	0.00	31.17	1.84
	partitions	60	60	30	42	10.33	0.43	0.00	0.00	13.74	0.58
	doors	2	2	0	2	10.05	0.02	0.00	0.00	11.81	0.02
	windows	18	0	0	18	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	118.8	118.8	0	118.8	11.81	1.40	0.00	0.00	11.81	1.40
	furniture					1.06	0.46				0.46
Total							11.46				20.13

Summary Building Elements

Element	Tot Area m2	Net Area m2	Material	Thickns m
floor	435.6	304.92	brick	0.05
walls	434	272	adobe	0.30
partitions	120	84	wood	0.10
doors	10	10	wood	0.05
windows	84	84	glass	6 mm
ceiling	451.8	451.8	wood	0.05

Building Totals

Area m2	Height m	Volume m3	Mass/ Floor	Glass/ Floor
435.6	4.5	1372.14	3.33	0.19

Building:	Office 1

2 Enter Heat Gain and Temperature Data

	Internal Gains								Temp Data	
	equipm (W/m2)	lighting W/m2	occupants N	total W/m2	gain rate (kW)	duration (hrs)	Qi/day (kWh)	Tot-Gains kWh/day	Ave Ext Temp C	N-Vent ACH
Summer	7	7	20	19.05	8.30	10	**82.98**			
Winter	7	7	20	19.07	8.28	10	**82.76**			
	Solar Gains									
	direct rad W/m2	diffuse rad W/m2	glazing area m2	transmtnc factor	gain rate (kW)	duration hrs	Qs/day kWh			
Summer	0	111	72	0.8	6.39	14	**89.51**	**172.49**	28	1
Winter	222	78	72	0.8	17.28	9	**155.52**	**238.28**	9.4	1

3 Calculation Results

		Warm Period	Cool Period
Internal Temperature Swing	**(K)**	**9.18**	**7.22**
Mean Internal Temperature	(C)	30.46	20.01
Peak Internal Temperature	(C)	35.06	23.62

4 Support Tables

Calculation of Enhancement Factor

space	surface	solar day fraction (f)	absorbance a	enhance factor
4	brick wall	0.8	0.4	**1.32**
5	conc-floor	0.5	0.6	**1.30**
6	conc-floor	0.5	0.6	**1.30**
5	conc-floor	0.5	0.6	**1.30**
0	0	0	0	**1.00**

Heat Loss Rates

Period	HL-fab W/K	HL-vent W/K	HLC W/K	HLC W/K
Warm	684.62	452.81	1137.43	2.61
Cool	483.02	452.81	935.83	2.15

dhc Library for Various Materials (W/m2 K)

dhc type	thickness m	granite	concrete	brick	wood	adobe	limestone	ceramic	sand
direct	0.05	31.46	28.33	24.59	11.81	22.26	31.34	30.43	16.47
	0.10	59.39	36.34	34.52	13.74	35.20	52.07	55.13	23.51
	0.15	73.81	49.65	41.05	12.49	34.35	52.81	62.86	21.69
	0.20	74.10	51.10	37.76	12.32	31.91	49.00	59.90	20.55
	0.30	67.06	45.70	36.62	12.38	31.17	47.07	54.96	20.50
	0.40	65.35	44.29	36.79	12.38	31.34	47.30	54.79	20.55
indirect	0.05	21.80	18.10	18.34	10.05	17.03	21.07	21.18	13.57
	0.10	25.61	21.92	20.16	10.33	19.36	23.05	24.36	15.16
	0.15	25.27	21.77	19.76	9.54	18.11	21.80	23.62	13.97
	0.20	24.42	21.46	18.62	9.48	17.32	20.95	22.66	13.51
	0.30	23.34	20.03	18.62	9.54	17.26	20.72	21.92	13.57
	0.40	23.28	19.93	18.17	9.54	17.26	20.78	21.97	13.57

Diurnal Heat Capacity Calculation Worksheet	Building Name:	Office 2
	Location:	Seville

1 Enter Building Mass Data

building information						DHC for summer		DHC for winter calculations			
space	building element	total area m2	subtract windows	covered fraction %	net area m2	dhc W/m2K	DHC kW/K	sunlit area m2	enhance factor	dhc W/m2K	DHC kW/K
	floor	39.6	39.6	30	27.72	0.00	0.00	0.00	0.00	21.92	0.61
	walls	64.2	58.2	20	46.56	20.16	0.94	0.00	0.00	20.16	0.94
1	partitions	0	0	20	0	0.00	0.00	0.00	0.00	0.00	0.00
	doors	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
	windows	6	0	0	6	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	39.6	39.6	0	39.6	51.10	2.02	0.00	0.00	51.10	2.02
	floor	39.6	39.6	30	27.72	0.00	0.00	0.00	0.00	21.92	0.61
	walls	64.2	56.2	20	44.96	20.16	0.91	0.00	0.00	20.16	0.91
3	partitions	0	0	20	0	0.00	0.00	0.00	0.00	0.00	0.00
	doors	2	2	0	2	10.05	0.02	0.00	0.00	13.74	0.03
	windows	6	0	0	6	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	39.6	39.6	0	39.6	51.10	2.02	0.00	0.00	51.10	2.02
	floor	118.8	118.8	30	83.16	0.00	0.00	0.00	0.00	21.92	1.82
	walls	118.4	78.4	20	62.72	20.16	1.26	18.00	1.32	34.52	2.36
4	partitions	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
	doors	4	4	0	4	10.05	0.04	0.00	0.00	13.74	0.05
	windows	36	0	0	36	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	135	135	0	135	51.10	6.90	0.00	0.00	51.10	6.90
	floor	118.8	118.8	30	83.16	0.00	0.00	8.00	1.30	21.92	1.88
	walls	93.6	73.6	20	58.88	20.16	1.19	0.00	0.00	34.52	2.03
5	partitions	60	60	30	42	20.16	0.85	0.00	0.00	20.16	0.85
	doors	2	2	0	2	10.05	0.02	0.00	0.00	13.74	0.03
	windows	18	0	0	18	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	118.8	118.8	0	118.8	51.10	6.07	0.00	0.00	51.10	6.07
	floor	118.8	118.8	30	83.16	0.00	0.00	8.00	1.30	21.92	1.88
	walls	93.6	73.6	20	58.88	20.16	1.19	0.00	0.00	34.52	2.03
6	partitions	60	60	30	42	20.16	0.85	0.00	0.00	20.16	0.85
	doors	2	2	0	2	10.05	0.02	0.00	0.00	13.74	0.03
	windows	18	0	0	18	0.00	0.00	0.00	0.00	0.00	0.00
	ceiling	118.8	118.8	0	118.8	51.10	6.07	0.00	0.00	51.10	6.07
	furniture					1.06	0.46				0.46
Total							30.82				40.44

Summary Building Data **Building Totals**

Element	Tot Area m2	Net Area m2	Material	Thickns m	Area m2	Height m	Volume m3	Mass/ Floor	Glass/ Floor
floor	435.6	304.92	concrete	0.10					
walls	434	272	brick	0.10					
partitions	120	84	brick	0.10	435.6	4.5	1372.14	3.33	0.19
doors	10	10	wood	0.05					
windows	84	84	glass	6 mm					
ceiling	451.8	451.8	concrete	0.20					

Building:	Office 2

2 Enter Heat Gain and Temperature Data

	Internal Gains								Temp Data	
	equipm (W/m2)	lighting W/m2	occupants N	total W/m2	gain rate (kW)	duration (hrs)	Qi/day (kWh)	Tot-Gains kWh/day	Ave Ext Temp C	N-Vent ACH
Summer	7	7	20	19.05	8.30	10	**82.98**			
Winter	7	7	20	19.07	8.28	10	**82.76**			
	Solar Gains									
	direct rad W/m2	diffuse rad W/m2	glazing area m2	transmtnc factor	gain rate (kW)	duration hrs	Qs/day kWh			
Summer	0	111	72	0.8	6.39	14	**89.51**	**172.49**	28	1
Winter	222	78	72	0.8	17.28	9	**155.52**	**238.28**	9.4	1

3 Calculation Results

		Warm Period	Cool Period
Internal Temperature Swing	**(K)**	**3.41**	**3.59**
Mean Internal Temperature	(C)	30.43	19.86
Peak Internal Temperature	(C)	32.14	21.65

4 Support Tables

Calculation of Enhancement Factor

space	surface	solar day fraction (f)	absorbance a	enhance factor
4	brick wall	0.8	0.4	**1.32**
5	conc-floor	0.5	0.6	**1.30**
6	conc-floor	0.5	0.6	**1.30**
5	conc-floor	0.5	0.6	**1.30**
0	0	0	0	**1.00**

Heat Loss Rates

Period	HL-fab W/K	HL-vent W/K	HLC W/K	HLC W/K m2
Warm	698	453	1151	2.64
Cool	497	453	950	2.18

dhc Library for Various Materials (W/m2 K)

dhc type	thickness m	granite	concrete	brick	wood	adobe	limestone	ceramic	sand
direct	0.05	31.46	28.33	24.59	11.81	22.26	31.34	30.43	16.47
	0.10	59.39	36.34	34.52	13.74	35.20	52.07	55.13	23.51
	0.15	73.81	49.65	41.05	12.49	34.35	52.81	62.86	21.69
	0.20	74.10	51.10	37.76	12.32	31.91	49.00	59.90	20.55
	0.30	67.06	45.70	36.62	12.38	31.17	47.07	54.96	20.50
	0.40	65.35	44.29	36.79	12.38	31.34	47.30	54.79	20.55
indirect	0.05	21.80	18.10	18.34	10.05	17.03	21.07	21.18	13.57
	0.10	25.61	21.92	20.16	10.33	19.36	23.05	24.36	15.16
	0.15	25.27	21.77	19.76	9.54	18.11	21.80	23.62	13.97
	0.20	24.42	21.46	18.62	9.48	17.32	20.95	22.66	13.51
	0.30	23.34	20.03	18.62	9.54	17.26	20.72	21.92	13.57
	0.40	23.28	19.93	18.17	9.54	17.26	20.78	21.97	13.57

Building:	Office 2

2 Enter Heat Gain and Temperature Data

	Internal Gains								Temp Data	
	equipm (W/m2)	lighting W/m2	occupants N	total W/m2	gain rate (kW)	duration (hrs)	Qi/day (kWh)	Tot-Gains kWh/day	Ave Ext Temp C	N-Vent ACH
Summer	7	0	20	12.05	5.25	10	**52.49**			
Winter	7	7	20	19.07	8.28	10	**82.76**			
	Solar Gains									
	direct rad W/m2	diffuse rad W/m2	glazing area m2	transmtnc factor	gain rate (kW)	duration hrs	Qs/day kWh			
Summer	0	111	72	0.8	6.39	14	**89.51**	**142.00**	28	20
Winter	222	78	72	0.8	17.28	9	**155.52**	**238.28**	9.4	1

3 Calculation Results

		Warm Period	Cool Period
Internal Temperature Swing	**(K)**	**6.52**	**3.59**
Mean Internal Temperature	(C)	27.31	19.86
Peak Internal Temperature	(C)	30.57	21.65

4 Support Tables

Calculation of Enhancement Factor

space	surface	solar day fraction (f)	absorbance a	enhance factor
4	brick wall	0.8	0.4	**1.32**
5	conc-floor	0.5	0.6	**1.30**
6	conc-floor	0.5	0.6	**1.30**
5	conc-floor	0.5	0.6	**1.30**
0	0	0	0	**1.00**

Heat Loss Rates

Period	HL-fab W/K	HL-vent W/K	HLC W/K	HLC W/K m2
Warm	698	9056	9754	22.39
Cool	497	453	950	2.18

dhc Library for Various Materials (W/m2 K)

dhc type	thickness m	granite	concrete	brick	wood	adobe	limestone	ceramic	sand
direct	0.05	31.46	28.33	24.59	11.81	22.26	31.34	30.43	16.47
	0.10	59.39	36.34	34.52	13.74	35.20	52.07	55.13	23.51
	0.15	73.81	49.65	41.05	12.49	34.35	52.81	62.86	21.69
	0.20	74.10	51.10	37.76	12.32	31.91	49.00	59.90	20.55
	0.30	67.06	45.70	36.62	12.38	31.17	47.07	54.96	20.50
	0.40	65.35	44.29	36.79	12.38	31.34	47.30	54.79	20.55
indirect	0.05	21.80	18.10	18.34	10.05	17.03	21.07	21.18	13.57
	0.10	25.61	21.92	20.16	10.33	19.36	23.05	24.36	15.16
	0.15	25.27	21.77	19.76	9.54	18.11	21.80	23.62	13.97
	0.20	24.42	21.46	18.62	9.48	17.32	20.95	22.66	13.51
	0.30	23.34	20.03	18.62	9.54	17.26	20.72	21.92	13.57
	0.40	23.28	19.93	18.17	9.54	17.26	20.78	21.97	13.57

The comparison between the two versions of the example building illustrates the significance of thermal mass effects. For example, the selection of building materials in *office 1* showed how detrimental some finishes such as wood can be for the performance of the element. The inadequate diurnal heat capacity of such elements result in large swings and consequently in high peak temperatures. The introduction of building components of materials with higher *dhc* values as shown in *office 2,* helped to reduce the internal swings by about 60%. If additional measures are taken in order to minimize heat gains and promote heat loss by night ventilation as illustrated in the last worksheet, the internal conditions can be further improved. Internal temperature swings tend to increase with night ventilation but because the mean internal temperature decreases, the room results in lower peaks during the day. Temperature swings can be further reduced by using materials with higher *dhc* for walls and ceilings, or/and by increasing the area of all exposed walls and internal partitions. These are measures which have to be considered in relation to other design requirements of the building. The importance of minimising internal heat gains by optimising daylighting had a distinct importance on the thermal results.

8.4 Quantitative Guidelines

According to the above discussion guidelines for the use of thermal mass can be provided in terms of the diurnal heat capacity required to limit internal temperature swings. The required *DHC* to limit temperature swings to a defined range can be estimated as a function of the total heat gain of the building during the day. For example, the required *DHC* to maintain temperature swings within 5 K for can be determined as follows:

$$DHC = 0.61 * \Phi t / 5 ,$$

where, Φt = the total daily heat gain of the room

For a building with a heat gain value of 60 kWh/day the *DHC* which ensures that the internal temperatures swing will range within 5 K would be,

$$DHC = 0.61 * 60/5 = 7.32 \text{ kW/K}$$

8.4.1 Effect of Surface Area

If we consider that the *DHC* increases with surface area, it is possible to relate a defined temperature swing with a minimum heat exchanging mass surface area of a particular room. This relation can be given in terms of exposed mass surface area per unit of heat gain. As discussed in section 3.3, there is an optimum thickness in terms of the diurnal heat capacity according to the characteristics of the material used. If an optimum thickness is found the required *DHC* to attain a defined swing will depend on the area of the heat exchanging surfaces and the total heat gain.

Table 8.1 lists the resultant mass surface area required to obtain the necessary *DHC* that prevents the temperature swing of a room from exceeding 5 K. Values are given for various heat gain rates and different materials. The external envelope is assumed well insulated on the outside and the internal surfaces accounted for should be totally exposed to the internal air.

Table 8.1
Mass Surface Area per Heat Gain Unit Required for Limiting Internal Swings to 5 K

heat gain kWh/day	*DHC kW/K*	*total area of exposed mass surface m^2*							
		concrete 200 mm		*brick 150 mm*		*adobe 100 mm*		*hollow block 150 mm*	
		direct	*indirect*	*direct*	*indirect*	*direct*	*indirect*	*direct*	*indirect*
6	0.73	10.6	27	18	35	20.1	38	21.5	39
12	1.46	21	61	36	70	41.6	75.8	43	78
60	7.32	106	306	180	350	208	379	215	389
120	14.64	212	611	360	700	416	758	430	779
240	29.28	425	1221	720	1401	832	1516	859	1558

The *dhc* values used for the calculation of *DHC* for each material are those of tables A2.3 and A2.4, in Appendix A2. The values given in the table above are for homogeneous single layered elements with no additional finishes.

If an approximate heat gain rate of a room can be anticipated during the design process, with the use of the values provided in table 8.1 it is possible to estimate the resultant temperature swing. This simple relation applies especially for single spaces where all the surfaces have the same type of thermal exchange. When the internal layout of the building includes various rooms and the nature of heat exchange of the surfaces is variable, each surface would have to be looked at individually assigning the of *dhc* values as appropriate. The example building was used to illustrate these cases.

8.5 Summary Recommendations

Optimisation of thermal mass in buildings should be a design target in order to avoid large internal temperature swings. Materials with large thermal capacity i.e. that the product of their density and specific heat is large, should be used. Low conductive materials for internal surfaces such as woods and other finishes should be avoided because they can impede the flow of heat through into the inner portions of the elements. The diurnal heat capacity can be used as an indicator of the performance of the thermal mass in buildings both for the cool and the warm periods.

8.5.1 Exposure

The envelope of buildings should be well insulated on the outside especially in locations of large temperature variations. In situations of smaller external swings, envelopes with reflective external surfaces may be used to minimise conductive gains through the building fabric. In all cases, during the overheating season total exclusion of direct solar radiation should be ensured. Measures for shading should be considered bearing in mind the requirements for daylighting. The internal surfaces of the massive elements should have a large exposure to the internal air. Covered portions of massive surfaces, for example by furniture, rugs or carpets have little or no influence in the process of heat storage.

8.5.2 Thickness

Building elements of excessive thickness should be avoided since their contribution to heat storage and release within a 24 hour cycle may not only be small but can reduce the overall performance of the thermal mass resulting in larger swings. The optimum thickness of the material in terms of the diurnal heat capacity can be estimated. Larger quantities of mass are more effective when distributed over larger area of exposed surface. An optimum thickness from the point of view of the diurnal heat capacity may some times be impractical in structural terms, especially for very dense and conductive materials like concrete or stone. The greater thickness between the two requirements should then be chosen.

8.5.3 Location

If additional surface area is to be introduced into the building it is more effective to place it on internal elements of the room and preferably with both surfaces facing the interior. The thickness of the internal element should be of adequate dimension so that the benefits for heat storage and heat release are automatically doubled. The performance of internal mass is more effective, when positioned in walls, ceilings and especially internal partitions rather than on the floor. It is recommended that internal mass elements are constructed with massive materials and reflective surfaces to promote an even distribution of short wave radiation within the room, especially during winter when the use of solar gains may be required. Light colours also help in the distribution of daylight within the space.

8.5.4 Night Ventilation

For optimum performance, the internal surfaces of the room should have discharged as much heat as possible at the beginning of the storage cycle. Increased night ventilation rates are desirable to accelerate the process of heat dissipation from the internal surfaces. As the heat gains increase during the day, the need for night ventilation augments and in very hot weather often become the only mechanism to ensure that the process of heat storage-heat dissipation occur within the 24 hour cycle. Night ventilation can be provided naturally by placing openings toward the higher wind pressure areas. Openings placed high at the top of walls can be useful to promote night cooling from the surface of the ceiling which tends to be the warmer within rooms although air flow close to internal wall surfaces is also desirable.

8.5.5 Calculation Worksheet

A calculation worksheet is proposed here to facilitate the use of *DHC* values for internal temperature swing calculations. An example of its use is presented with data of an office building and temperature swings estimated for both warm and cool periods using different heat gain conditions and building materials. The worksheet can be used to determine the effect of the thermal mass of the building and the expected internal temperature variations as a function of external and internal heat gains. The procedure allows for the replacement of values to quickly estimate the effect of a number of mass variables. The calculations are limited to average values and no detailed hourly temperature profile is given. Results compared well with SERI-RES simulations. Values of *DHC* for different materials and thicknesses are given in library tables in worksheet and in Appendix 5.

9
Conclusions

Conclusions

The thermal mass of a building has a significant effect on its overall thermal performance. Due to its inertia effects, it reduces the temperature fluctuations of the external climate and tends to minimise peak internal temperatures in the warmer periods of the day when thermal discomfort is often experienced. The optimum use of thermal mass will have a considerable effect on the reduction of heating and cooling requirements and may help to optimise constructional costs.

Optimisation of thermal mass in buildings cannot be taken as an isolated functional design step but it should be approached in good integration with the total design strategy adopted according to the specific needs of each building and location. The optimisation of thermal mass depends largely on the optimisation of the thermal performance of the building as a whole. More specifically, if the building is not properly shaded during the high temperature periods, the optimum quantity, location and distribution of thermal mass will not eliminate on its own the risk of internal overheating.

The performance of the thermal mass of the building can be assessed in terms of the actual temperature profile obtained inside the rooms and in terms of the temperature swings as a function of the daily heat gains. The actual temperature cannot be predicted solely from the design of the building mass since it depends largely on the characteristics of the external climate. A number of variables of thermal mass distribution, location and quantity included in the plan of simulations in chapter 6 provided broad indication of the benefits of internal mass exposure for a single room using summer weather data for Seville. In most conditions, the increase of mass in terms of area exposed rather than on element thickness indicated significant thermal improvement on the internal climate of the room. This was also observed in the data obtained from thermal measurements in various buildings.

The evaluation of the effect of thermal inertia of the building with respect to the internal temperature swing is possible with the use of the diurnal heat capacity of the building and the total heat gain. For the overheating periods, assuming the building is shaded and the envelope well insulated, the internal heat gain and the total *DHC* can be used to predict internal swings in day-time occupied buildings. Similarly, the thermal performance of the building in the cooler months can be estimated with the daily solar gains through transparent elements. Recommendations for diurnal heat capacities and corresponding mass surface area to limit internal temperature swings for various heat gain rates is summarised in table 8.1 of the design guidelines in chapter 8. An example building is used to illustrate the *dhc* method and its application for different heat gain conditions.

A calculation worksheet used to facilitate the estimates is also presented. The temperature swing predictions of diurnal heat capacity both for the cool and warm periods were in close agreement with the simulations and the field measurements in four case study buildings.

For each material there is an optimum thickness that can be achieved in order to ensure that the heat storage-heat dissipation process has a duration of 24 hours. This is given by the penetration depth of the material expressed in equations (10), (11) and (12) of the thermal mass parameters in chapter 3. Depending on the properties of the materials, the optimum thickness may be different from that of the minimum structural requirements. In these situations, the greater value should be chosen. Once an optimum thickness has been estimated, the thermal performance will increase as the exposed mass surface area is increased provided the envelope is well insulated and solar gains excluded from the interior.

The exposure of mass surfaces is especially effective when it is provided on internal elements such as internal partitions. The amount of heat that can be stored in such building components can be doubled when both surfaces face the internal air. However, it should be borne in mind that when an optimum element thickness has been surpassed, the inner portions of these elements will not be effectively participating in the thermal exchanges within the room. Excess thickness on external walls may be detrimental as heat stored in the structure may take more than one day to reach the interior and will begin to flow outwards when the surface is again absorbing heat during the new day causing a reduction on the effective storage capacity of the building. In periods of overheating additional thickness may reduce internal swings but heat dissipation must be ensured with night ventilation.

Night ventilation is only worth considering firstly, if the building mass of the room is adequate and effectively located and distributed throughout the space and secondly, if the outdoor temperature fluctuation approaches or exceeds 10 K. In periods of humid and warm weather where this range may not be reached it is advisable to use fans directed to the internal surfaces to accelerate heat release at night-time.

Optimisation of thermal mass for indoor cooling should be one of the main objectives for non-domestic building design in predominantly warm climates. The optimum use of the building components can lead to improvements in the thermal characteristics of the building and help to rationalise the use of building materials. The efficient use of the building mass will lead to the reduction of internal temperature swings often the cause of thermal discomfort inside buildings.

Finally, the results of the experiments, thermal simulations and *dhc* calculations presented in this thesis were performed in relation to the specific climatic conditions of Seville. This climatic location is representative of many other predominantly warm regions around the world and the results may be a useful reference. However, the investigation of *dhc* effects in different conditions and other building materials could be the subject of further research. Additional studies may also include the treatment of multi-layered walls and a more detailed study of the effect of night ventilation on the diurnal heat capacity of elements in conditions of extreme hot weather.

Bibliography and References

1. Baer S. (1980), *Cooling with Night Air.* Alternative Sources of Energy Vol 41 Minnesota US Jan 1980 p.22
2. Baranaby R. (1980), *Structural Mass Cooling in a Commercial Building Using Hollow-Core Concrete Plank.* 5 National Passive Solar Conference, Amherst, Mass.
3. Sander- Barakat (1984), *Mass and Glass, How Much? How Little?* ASHRAE Journal Nov 1984 p.26
4. Shaviv E. (1988), *On the Determination of the Optimum Thermal Mass in the Mediterranean Climate.* Passive Solar Architecture Conference 1988 Bled, Jugoslavia pp 374-378.
5. Balcomb J. (1983), *Heat Storage and Distribution Inside Passive Solar Buildings.* Los Alamos, New Mexico, US.
6. Silvestrini G.(1988), *Cooling of Ancient Buildings Through Night Forced Ventilation.* PLEA 88, Lisbon Portugal. Conference Proceedings, Pergamon Press.
7. *Equations to Predict the Temperatures Inside a Night Ventilation Cooled Building on a Design Day.*
8. Stein B.& Reynolds J. (1992), *Thermal Control of Buildings.* Mechanical and Electrical Equipment for Buildings, 8 edition, New York.
9. Baer S. (1983), *Raising the Open U value by Passive Means.* National Passive Solar Conference Vol 8. US.
10. Crowther (1980), *Night Ventilation Cooling of Mass.* 5 National Passive Solar Conference, ASES inc. US.
11. Chandra S. & Keresteciogl u (1984), *Heat Transfer in Naturally Ventilated Rooms: Data from Full-scale Measurements.* ASHRAE Transactions 90 1B pp 221-225. US
12. Cook J.(Editor 1989), *Passive Cooling.* MIT Camb. Mass. US.
13. Pitts A. & Abro R. *Intelligent Control of Night-time Ventilation.* PLEA 91, Seville, Spain. Conference Proceedings.
14. Chandra S. et al (1986), *Cooling with Ventilation.* Solar Energy Research Institute. Fla, US.
15. Kammerud R. & Anderson B.(1984), *Ventilation Cooling of Residential Buildings.* ASHRAE Transactions Vol 90 (1B).
16. Van der Maas J. & Roulet C. (1991), *A Simple Model for the Estimation of Potential Cooling by Night-time Ventilation.* PLEA 91, Seville, Spain. Conference Proceedings.

17. Parpasenos G. *Heat Attenuation and Thermal Mass Effect.* Workshop on Passive Cooling ISPRA.
18. Bejan A. (1984), *Convective Heat Transfer* p.45 NY.
19. Balaras C. (1992), *The Role of Thermal Mass on the Cooling Load of Buildings. An Overview of Computational Methods and Experimental Work within PASCOOL.* University of Athens. (unpublished).
20. Ford B. & Short A. (1988), *Passive Cooling of a New Brewery Process Building in Malta.* PLEA 88, Lisbon, Portugal. Conference Proceedings.
21. Balcomb J.& Hedstrom (1980), *Determining Heat Fluxes from Temperature Measurements made in Massive Walls.* 5 National Passive Solar Conference. Amherst, Mass. US. pp.136-140.
22. Perkings D. (1984), *Heat Balance Studies for Optimizing Passive Cooling with Ventilation Air.* ASHRAE Journal 26(2) pp. 27-29.
23. ASHRAE Handbook Fundamentals (1972) (1985).
24. Van der Maas J. & Roulet C. (1991), *Night-time Ventilation by Stack Effect.* ASHRAE Transactions 97 (part 1) p.516
25. Ford B. & Short A. (1993), *Passive Night Vent Cooling: Results from Field Measurements in Malta.* Solar Energy in Architecture and Urban Planning. Florence.
26. Balcomb J. (1983), *Estimating Temperature Swings in Direct Gain Buildings.* Passive Solar Handbook, NY.
27. Evans B. (1992), *Summer Cooling Using Thermal Capacity.* Report on BRE Research. AJ August 92, pp. 38-41.
28. Neeper D. Mc Farland R. (1982), *Some Potential Benefits of Funfdamental Research for the Passive Solar Heating and Cooling of Buildings.* Los Alamos National Laboratories, N.M., US.
29. Green C. & Wells J. (1991), *SPIEL V.4.8 Thermal Simulation Programme* Ecotech Design Ltd. Sheffield UK.
30. British Research Establishment BRE (1991), *BREEZE Ventilation Simulations*, Watford, UK.
31. Centre for Experimental and Numerical Thermoflow (1991), *QUICK A Thermal Design Tool Release 4.* CENT. University of Pretoria, South Africa.
32. Anglia Higher Education College, *DAYLIGHT , Daylight Calculations,* Department of the Build Environment, Essex. UK.
33. Lechner, N. Heating, (1991), *Cooling and Lighting - Design Methods for Architects.* (section: Passive Cooling) U.S.A.

34. Houghten, F.C. , Blackshaw, J.L, Pugh, E.M. and McDermott, P. (1932), *Heat Transmision, as Influenced by Heat Capacity and Solar Radiation*. ASHVE Transactions. 38:23-1279
35 Alford, J.C., Ryan, J.E. and Urban, F.O. (1939), *Effect of Heat Storage and Variation in Outdoor Temperature and Solar Intensity on Heat Transfer Through Walls*. ASHVE Transactions. 45 : 369-396
36. Mackey, C.O. and Wright, L.T. (1944), *Periodic Heat Flow - Homogeneous Walls and Roofs*. Heating, Piping and Air Conditioning. September 546-555, also ASHVE Transactions. 50 : 293.
37. Milbank & Harrington-Lyn (1974), *Thermal Response and the Admittance Procedure*. The Building Services Engr. (J IHVE) 42 : 38-51 and BRE CP. 61/74.
38. Szokolay S.V. (1991), *Thermal Response of Buildings, Understanding the Admittance Procedure*. Architectural Science Unit University of Quensland, Qld. Australia.
39. Stewart, J.P. (1948), *Solar Heat Gains Through Walls and Roofs for Cooling Load Calculations*. ASHVE Transactions. 54 : 361-388
40. Stephenson, D.G. (1962), *Methods of Determining Non-steady State Heat Flow Through Walls and Roofs of Buildings*. J IHVE. 30 : 64-73 (May).
41. Danter, E. (1960), *Periodic Heat Flow Characteristics of Simple Walls and Roofs*. J IHVE 28 : 136-145
42. Loudon, A.G. (1968), *Summertime Temperatures in Buildings*. BRS.CP.37 47/68
43. Petherbridge, P. (1974), *Limiting Temperatures in Naturally Ventilated Buildings in Warm Climates*. BRE.CP 7/74
44. Burberry, P. (19..), *Practical Thermal Design in Buildings*, Batsford Academic and Educational Ltd, London.
45. Davis, M.G. (1973), *The Thermal Admittance of Layerd Walls*, Buiding Science 8, pp. 207-220.
46. Van der Maas K. (1993-94), Private comunication.
47. Van der Maas K. (1994), Leso-TMS and Pre-TMS. Spreadsheets for the calculation of thermal response of single zoned rooms.
48. Mathews, E.H., Rosseau, P.G., Richards, P.G., Lombard, C. (1991), *A Procedure to Estimeate the Effective Heat Storage Capability of a Building*. Building and Environment vol-26 N2. pp179-188.
49. Mathews, E.H. and Lombard, C. (1991), *An Efficient Procedure for Finding the Steady State Solution of Periodic, Time-Variable Heat Transfer Systems*. Centre for Experimental and Numerical Thermoflow, CENT. University of Pretoria, South Africa.

50. Givoni, B. *Man Climate and Architecture*, (1976), 2nd edition pp. 414-450, and (1981). Applied Science, London
51. SERI-RES Version 1.0, (1981), US Solar Energy Research Insititue, Golden, Colorado.
52. Haves, P. and Littler, J. (1987), Refinements to SERI-RES, Energy Technology Support Unit. UK Department of Energy, Report S-1130.
53. Balcomb J. (1982), *Heat Storage Effectiveness of Concrete Masonry Units* . Concrete Masonry Solar Architecture Quarterly, 2, No.2.
54. Fanger, P.O. (1970), *Thermal Comfort* Danish Technical Press.
55. Humphreys M. (1978), *Outdoor Temperature and Comfort Indoors.* Building Research and Practice Vol 2 (2).
56. Baker N. (1993). *Comfort Thermal and Visual.* Solar Energy and Buildings. Symposium Proceedings.
57. Orel, B. Macek, M. (1993), *Advanced Phase Change Materials for Heat Storage Applications in Buildings.* 3rd European Conference on Architecture, Florence. Conference Proceedings.
58. Pinney A. (1990). *The Effect of Thermal Node Placement on Predicted Energy Consumption and Internal Temperatures in the Program SERI-RES.* Building Research Station, Research Report 12.
59. Evans, M. (1980). *Housing, Climate and Comfort.* Architectural Press Ltd. London
60. Van der Maas J. & Roulet C. (1991), *Experimental Characterization of the Transient Thermal Behaviour of a Building Zone.* 2nd PASCOOL meeting in Glasgow, UK, February 15-18-1993
61. Van der Maas J. & Roulet C. (1991), *Working Document on Ventilation, Thermal Mass, Comfort and Solar Control.* 1st PASCOOL meeting in Lyon, France, November 23-26 ,1992.
62. Santamouris, M. and Argiriou, A. (1993), *The CEC Project PASCOOL.* Solar Energy in Architecture and Urban Planning. Florence, Italy.
63. Maldonado, E. and Goncalves H., (1993), *Case Study for the Evaluation of Thermal Mass Simulations Models.* 2nd PASCOOL meeting in Glasgow, UK, February 15-18-1993
64. Milbank, N., (1974), *A new Approach to Predicting the Thermal Environment in Buildings at the Early Design Stage.* Building Research Establishment Current Paper, UK.
65. Baker N. (1993). *Comfort and Passive Cooling.* Workshop on Passive Cooling ISPRA.
66. Halcrow Gilbert Associates Ltd. (1989), *Passive Solar Design Studies in Non-Domestic Buildings,* Section 5 Ventilation and Air Conditioning. UK.

67. Arens, E. A. *New Bio-climatic Chart for Environmental Design.* Conference Proceedings Edited by E.D Fernandes, Woods & Faust.
68. Szokolay S.V. (1984), *Passive and Low Energy Design for Thermal and Visual Comfort.* Proceedings of PLEA 84, Mexico.
69. INETER (1985). *Regimen Climatico de Managua.* Instituo Nicaraguense de Estudios Territoriales. Nicaragua.
70. Roy, L. (1979) *Underground Houses.* Stearling Publishing Inc. NY.
71. Balcomb J., Kosiewicz C., Lazarus G., McFarland D., and Wray O. (1982). *Passive Solar Design Handbook.* US Department of Energy report DOE/CS-0127/3.
72. Goldfinger M., (1993). *Villages in the Sun.* Praeger, NY.
73. Morley, S. Brainerd, G. (1978). *The Ancient Maya.* Stanford University Press, Stanford, California.
74. Cabeza, J.M. (1991) *Daylight Studies for Domes* PLEA 91, Seville, Spain. Conference Proceedings.

10

Appendices

A1 Diurnal Heat Capacity of Elements of Reference Cube

The calculation procedure that follows is that of refs. [5] and [26] described in chapter 7. The values of magnitude and phase for each wall type or thickness were taken from table A10.1

A1.1 Cube Structure: Concrete

Properties of Concrete:

density (ρ) = 2100 kg/m^3
conductivity (λ) = 1.40 W/m K
specific heat (c) = 0.181 (0.653) kJ/kg K

from equation (3), admittance (Y):

$$Y_\infty = \sqrt{2\pi\,\lambda\rho c/P} = 11.7 \text{ W/m}^2\text{.K}$$

A1.1.2 dhc for Concrete Structure - Direct Coupling

using equation (4), optimum thickness (xo)

$$x = \sqrt{\lambda P/\pi\rho c} = 0.16 \text{ m}$$

$$xo = 1.18 \times 0.16 = 0.196 \text{ m}$$

then, the dhc for an infinite wall,

$$dhc_\infty = \sqrt{\lambda\rho c P/2\pi} = 44.8 \text{ W/m}^2\text{.K}$$

and equation (5) for the dimensionless thickness (ξ),

$$\xi = x / \sqrt{P\lambda/\pi\rho c}$$

Direct dhc - *envelope thickness: 0.10*

ξ = 0.10/0.16 = 0.60
mag = 0.816
phase = 76.7°
dhc = 44.8 x 0.816 = 36.60 W/m^2 K

Direct dhc - *envelope thickness: 0.20*

ξ = 0.20/0.16 = 1.21
mag = 1.14
phase = 52°
dhc = 44.8 x 1.14 = 51.1 W/m^2 K

Direct dhc - *envelope thickness: 0.40*

ξ = 0.40/0.16 = 2.42
mag = 0.998
phase = 44.1°
dhc = 44.8 x 0.998 =44.2 W/m^2 K

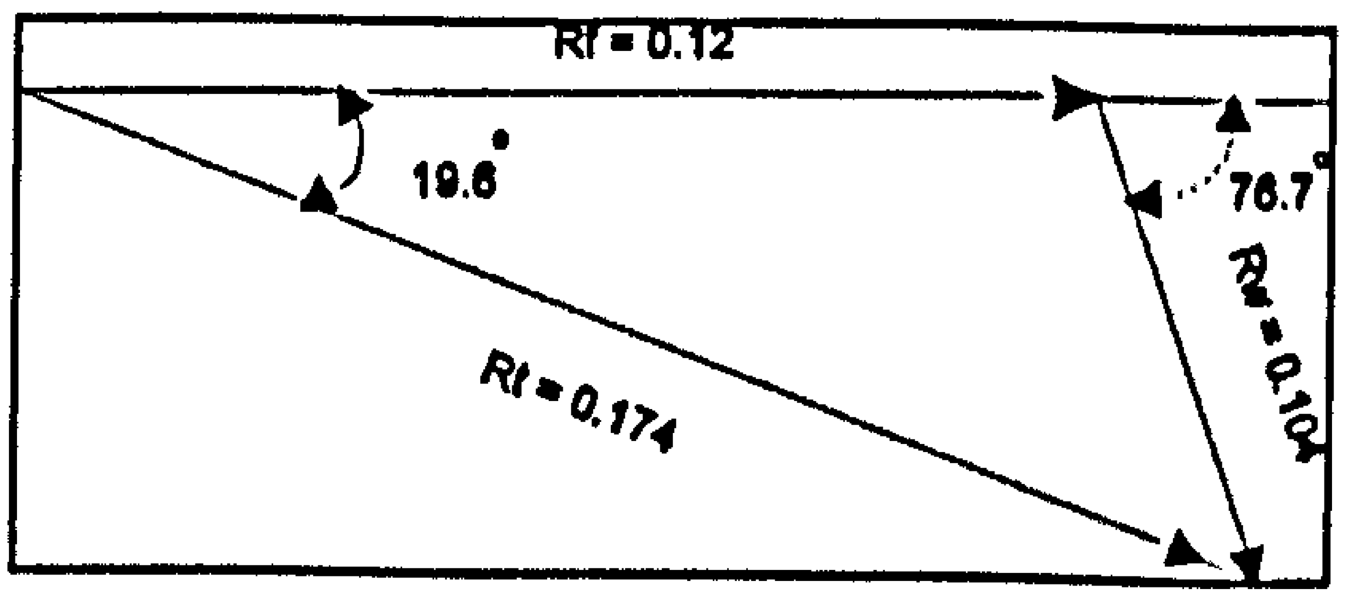
Direct dhc optimum thickness 0.196

ξ = 0.196/0.16 = 1.17
mag = 1.143
phase = 53.3°
dhc = 44.8 x 1.143 = 51.2 W/m^2 K

A1.1.3 dhc for Concrete Structure - Indirect Coupling

***Indirect dhc** - envelope thickness: 0.10*

Wall Admittance:	
11.7 x 0.816	= 9.53 W/m^{2}K
Air Film Resistance	= 0.12 m^2 K/W
Wall Resistance	= 0.104 m^2 K/W
Phase Lag	=76.7° (5 hrs 6 min)
Series Resistance	= 0.174 m^2 K/W
Series Admittance	= 5.73 W/m^{2}K

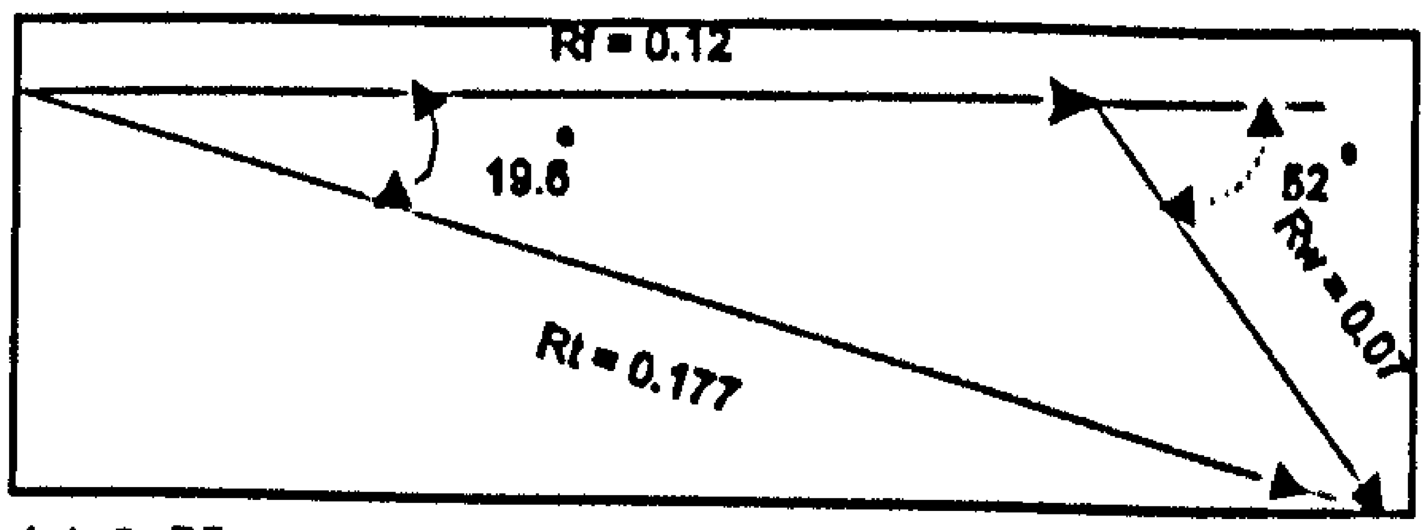


A.1.1 Vector sum of the resistance of the air film plus the resistance of the wall for a 0.10 m concrete structure.

Then, *dhc* = 3.82 x 5.73 = 21.9 W/m^2 K

***Indirect dhc** - envelope thickness: 0.20*

Wall Admittance:	
11.7 x 1.14	= 13.2 W/m^{2}K
Air Film Resistance	= 0.12 m^2 K/W
Wall Resistance	= 0.07 m^2 K/W
Phase Lag	= 52° (3 hrs 35 min)
Series Resistance	= 0.177 m^2 K/W
Series Admittance	= 5.62 W/m^{2}K.

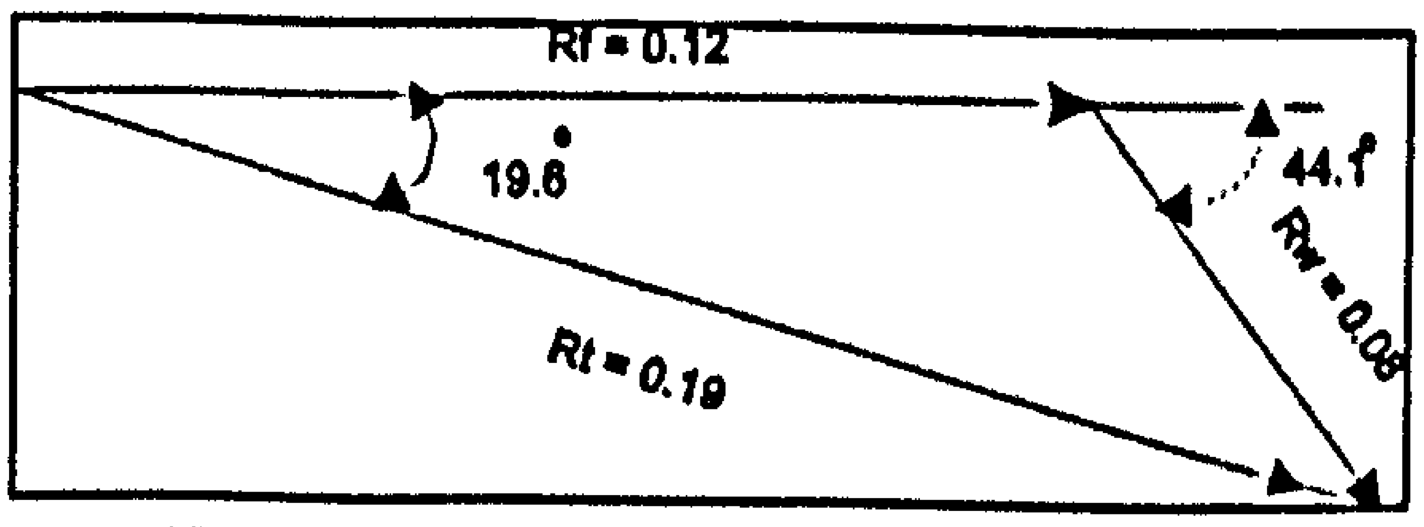


A1.2 Vector sum of the resistance of the air film plus the resistance of the wall for a 0.20 m concrete structure

Then, *dhc* = 3.82 x 5.62 = 21.4 W/m^2 K

***Indirect dhc** - envelope thickness: 0.40*

Wall Admittance	
11.7 x 0.998	= 11.6 W/m^{2}K
Wall Resistance	= 0.08 m^2 K/W
Air Film Resistance	= 0.12 m^2 K/W
Phase Lag	= 44°(2 hrs 55 min)
Series Resistance	= 0.19 m^2 K/W
Series Admittance	= 5.26 m^2 K/W.



A1.3 Vector sum of the resistance of the air film plus the resistance of the wall for a 0.20 m concrete structure

Then, *dhc* = 3.82 x 5.26 = 20 W/m^2 K

A.1.1.4 Diurnal Heat Capacity for Brick Structure

Properties of Brick:

density (ρ) = 1700 Kg/m^3
conductivity (λ) = 0.84 W/m K
specific heat (c) = 0.222 (0.800) kJ/kg K

from equation (3), admittance (Y):

$Y_\infty = \sqrt{2\pi\,\lambda\rho c/P} = 9.08\ W/m^2K$

using equation (4), optimum thickness (xo)

$x = \sqrt{\lambda P/\pi\rho c} = 0.13\ m$

$xo = 1.18 \times 0.13 = 0.15\ m$

the dhc for an infinite wall,

$dhc_\infty = \sqrt{\lambda\rho c P/2\pi} = 34.7\ W/m^2K,$

and equation (5) for the dimensionless thickness (ξ),

A1.2.1 dhc for Brick Structure - Direct Coupling

Direct dhc - envelope thickness: 0.10

ξ = 0.10/0.15 = 0.78
mag = 0.996
phase = 68.7°
dhc = 34.7 x 0.996 = 34.5 $W/m^2.K$

Direct dhc - envelope thickness: 0.20

ξ = 0.20/0.15 = 1.55
mag = 1.09
phase = 45.2°
dhc = 34.7 x 1.09 = 37.7 $W/m^2 K$

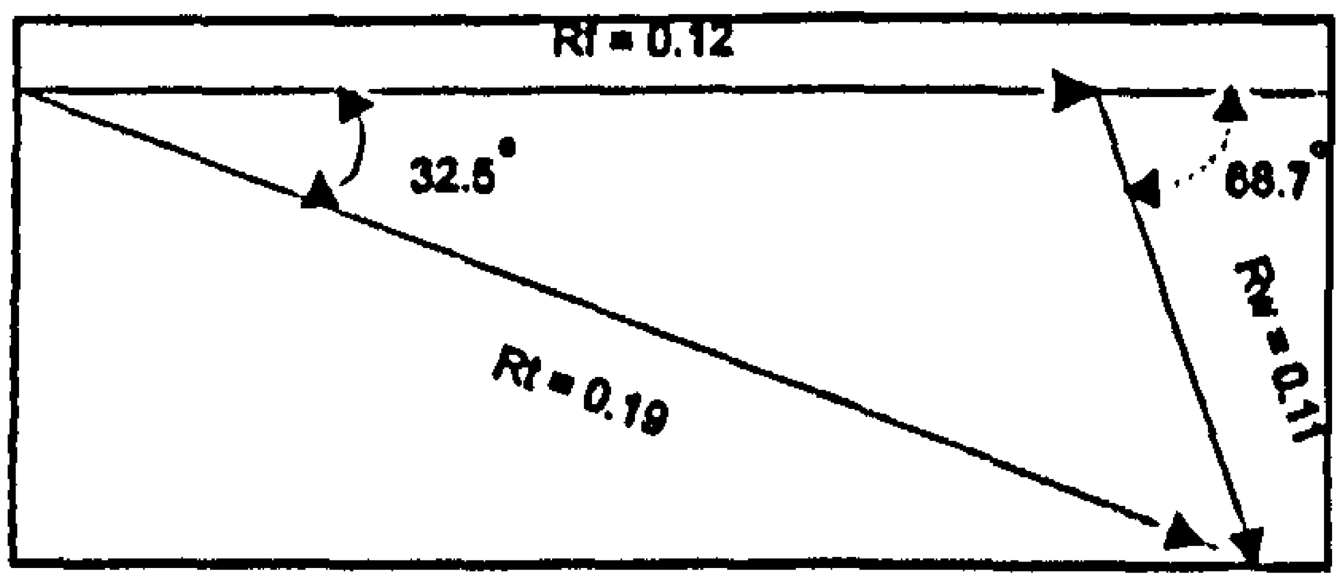
Direct dhc - envelope thickness: 0.40

ξ = 0.40/0.15 = 3.11
mag = 0.996
phase = 45.0°
dhc = 34.7 x 0.996 = 34.5 $W/m^2 K$

A1.2.2 dhc for Brick Structure - Indirect Coupling

***Indirect dhc** - envelope thickness: 0.10*

Wall Admittance	
9.08 x 0.996	= 9.02 W/K m^2
Air Film Resistance	= 0.12 m^2 K/W
Wall Resistance	= 0.11 m^2 K/W
Phase Lag	= 68.7°:3 hrs 6 min
Series Resistance	= 0.19 m^2 K/W
Series Admittance	= 5.31 W/K m^2
Phase Lag	= 32.5°: 3 hrs 6 min



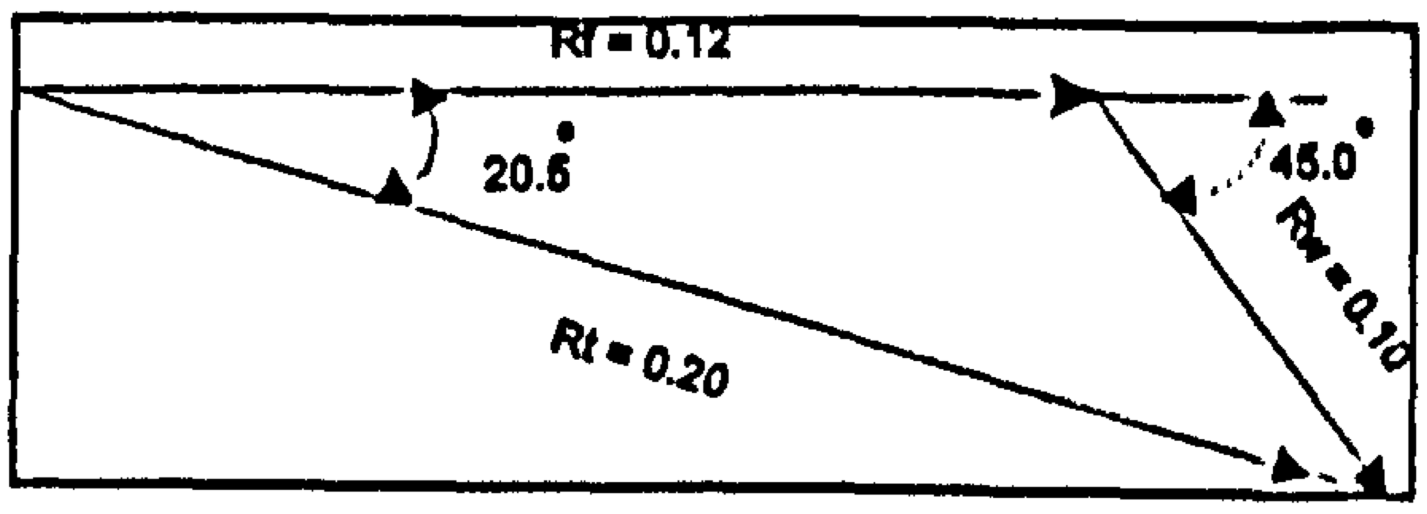
A1.4 Vector sum of the resistance of the air film plus the resistance of the wall.

dhc (i) = $(P/2\pi)Y$

Then, *dhc* = 3.82 x 5.31 = 20.3 W/m^2.K

***Indirect dhc** - envelope thickness: 0.20*

Wall Admittance:	
9.08 x 1.09	= 9.9 W/ K m^2
Air Film Resistance	= 0.12 m^2 K/W
Wall Resistance	= 0.10 m^2 K/W
Phase Lag	= 45.2° 3 hrs 6 min.
Series Resistance	= 0.20 m^2 K/W
Series Admittance	= 5.0 W/K m^2
Phase Lag	= 20.5° 3 hrs 6 min.



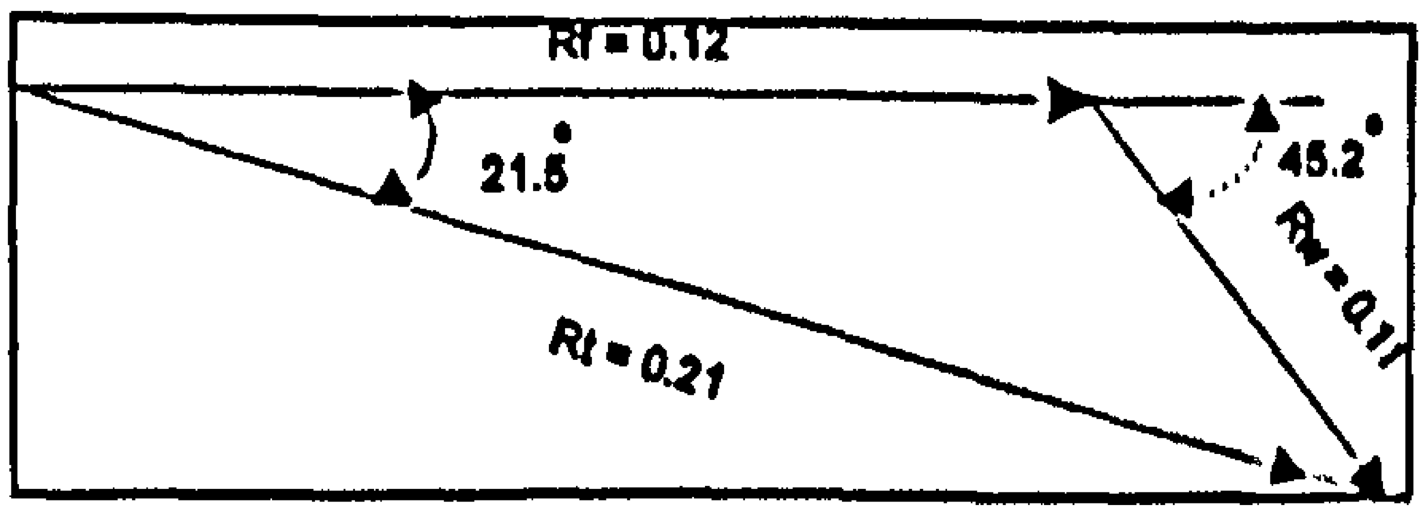
A1.5 Vector sum of the resistance of the air film plus the resistance of the wall.

dhc (i) = $(P/2\pi)Y$

Then, dhc = 3.82 x 5 = 19.1 W/m^2.K

***Indirect dhc** - envelope thickness: 0.40*

Wall Admittance	
9.08 x 0.996	= 9.02 W/ K m^2
Air Film Resistance	= 0.12 m^2 K/W
Wall Resistance	= 0.10 m^2 K/W
Phase Lag	= 45.0° 3 hrs 6 min.
Series Resistance	= 0.21 m^2 K/W
Series Admittance	= 0.15 W/K m^2
Phase Lag	= 21.5° 3 hrs 6 min.



A1.6 Vector sum of the resistance of the air film plus the resistance of the wall.

dhc (i) = $(P/2\pi)Y$

Then, dhc = 3.82 x 5 = 19.1 W/m^2.K

DHC for the Reference Zone

Table A2-3

Diurnal Heat Capacity for the Concrete Cube Types

	Surface	*Area* m^2	*dhc* W/m^2K *direct*	*dhc* W/m^2K *indirect*	*DHC* W/K *direct*	*DHC* W/K *indirect*
Envelope : 0.10 m	floor	64	36.3	21.9	2.32	1.40
	walls cube 1	128	36.3	21.9	4.64	2.80
	walls cube 2	124	36.3	21.9	4.50	2.71
	walls cube 3	119	36.3	21.9	4.31	2.60
	walls cube 4	110	36.3	21.9	3.99	2.40
	walls cube 5	98	36.3	21.9	3.55	2.14
	ceiling	64	36.3	21.9	2.32	1.40
	total cube 1	256	36.3	21.9	9.29	5.60
	total cube 2	252	36.3	21.9	9.14	5.51
	total cube 3	247	36.3	21.9	8.96	5.40
	total cube 4	238	36.3	21.9	8.63	5.21
	total cube 5	226	36.3	21.9	8.20	4.94
Envelope : 0.20 m	floor	64	51.1	21.5	3.27	1.37
	walls cube 1	128	51.1	21.5	6.54	2.75
	walls cube 2	124	51.1	21.5	6.33	2.66
	walls cube 3	119	51.1	21.5	6.08	2.55
	walls cube 4	110	51.1	21.5	5.62	2.36
	walls cube 5	98	51.1	21.5	5.00	2.10
	ceiling	64	51.1	21.5	3.27	1.37
	total cube 1	256	51.1	21.5	13.1	5.50
	total cube 2	252	51.1	21.5	12.9	5.41
	total cube 3	247	51.1	21.5	12.6	5.31
	total cube 4	238	51.1	21.5	12.2	5.11
	total cube 5	226	51.1	21.5	11.54	4.85
Envelope : 0.40 m	floor	64	44.2	20.1	2.82	1.28
	walls cube 1	128	44.2	20.1	5.65	2.57
	walls cube 2	124	44.2	20.1	5.48	2.49
	walls cube 3	119	44.2	20.1	5.25	2.39
	walls cube 4	110	44.2	20.1	4.86	2.21
	walls cube 5	98	44.2	20.1	4.33	1.96
	ceiling	64	44.2	20.1	2.82	1.28
	total cube 1	256	44.2	20.1	11.31	5.14
	total cube 2	252	44.2	20.1	11.13	5.06
	total cube 3	247	44.2	20.1	10.91	4.96
	total cube 4	238	44.2	20.1	10.51	4.78
	total cube 5	226	44.2	20.1	9.98	4.54

Table A2-4
Diurnal Heat Capacity for Brick Cube Types

	Surface	*Area* m^2	*dhc* W/m^2K		*DHC* kW/K	
			direct	*indirect*	*direct*	*indirect*
Envelope : 0.10 m	floor	64	34.5	20.1	2.20	1.28
	walls cube 1	128	34.5	20.1	4.41	2.57
	walls cube 2	124	34.5	20.1	4.27	2.49
	walls cube 3	119	34.5	20.1	4.10	2.39
	walls cube 4	110	34.5	20.1	3.79	2.21
	walls cube 5	98	34.5	20.1	3.38	1.96
	ceiling	64	34.5	20.1	2.20	1.28
	total cube 1	256	34.5	20.1	8.83	5.14
	total cube 2	252	34.5	20.1	8.69	5.06
	total cube 3	247	34.5	20.1	8.52	4.96
	total cube 4	238	34.5	20.1	8.21	4.78
	total cube 5	226	34.5	20.1	7.79	4.54
Envelope : 0.20 m	floor	64	37.7	18.6	2.41	1.19
	walls cube 1	128	37.7	18.6	4.82	2.38
	walls cube 2	124	37.7	18.6	4.67	2.30
	walls cube 3	119	37.7	18.6	4.48	2.21
	walls cube 4	110	37.7	18.6	4.14	2.04
	walls cube 5	98	37.7	18.6	3.69	1.82
	ceiling	64	37.7	18.6	2.41	1.19
	total cube 1	256	37.7	18.6	9.65	4.76
	total cube 2	252	37.7	18.6	9.50	4.68
	total cube 3	247	37.7	18.6	9.31	4.59
	total cube 4	238	37.7	18.6	8.97	4.42
	total cube 5	226	37.7	18.6	8.52	4.20
Envelope : 0.40 m	floor	64	34.5	18.1	2.20	1.15
	walls cube 1	128	34.5	18.1	4.41	2.31
	walls cube 2	124	34.5	18.1	4.27	2.24
	walls cube 3	119	34.5	18.1	4.10	2.15
	walls cube 4	110	34.5	18.1	3.79	1.99
	walls cube 5	98	34.5	18.1	3.38	1.77
	ceiling	64	34.5	18.1	2.20	1.15
	total cube 1	256	34.5	18.1	8.83	4.63
	total cube 2	252	34.5	18.1	8.69	4.56
	total cube 3	247	34.5	18.1	8.52	4.47
	total cube 4	238	34.5	18.1	8.21	4.30
	total cube 5	226	34.5	18.1	7.79	4.09

A3 Internal Temperature Swings

The calculations of the internal temperature swings for the reference zone with five different south facing window areas: 0, 4, 9,18 and 30 m^2 are presented here. The calculations were carried out for the cool and warm periods. For the warm period, the solar gain was excluded assuming the space is perfectly shaded, and the estimation is based on the internal heat gain assumed uniform at 3 kW during 12 hours of the day. The cool period performance was assessed with the solar gains corresponding to each different window area using solar radiation data of January for Seville. The temperature swings calculations were performed for three different thickness for each zone variant and for two different materials : concrete and brick.

A3.1 Calculations for Warm period and Cool Period

The heat gain rate is:

Warm Period Φi = 3 kW (12 h) = 36 kWh/day

Cool Period Φs = / x A (10 h) = 328 W/m^2 (10)

Φs = (3.28 kW/m^2 day) * (window area)

A3.2 Concrete Zone Types

A3.2.1 Envelope Thickness: 0.10 m

Zone Type 1 - window area : 0

a) warm period:

Φi = 36 kWh

from equation (11): swing = 36 (0.61) / 5.61 = 3.9 K.

no cool period calculation for this zone

Zone Type 2 - window area : 4 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.52 = 4.0 K

b) cool period

Φs = 3.28 (4) = 13.12, then swing = 13.12 (0.61) / 9.16 = 0.86 K

Zone Type 3 - window area: 9 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.41 = 4.1 K

b) cool period

Φs = 3.28 (9) = 29.52 kWh, then swing = 29.52 (0.61) / 8.97 = 2.0 K

Zone Type 4 - window area: 18 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.21 = 4.2 K

b) cool period

Φs = 3.28 (18) = 59.04 kWh, then swing = 59.04 (0.61) / 8.64 = 4.12 K

Zone Type 5 - window area: 30 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.95 = 4.4 K

b) cool period

Φs = 3.28 (30) = 98.4 kWh, then swing = 98.4 (0.61) / 8.21 = 7.2 K

A3.2.2 Envelope Thickness: 0.20 m

Zone Type 1 - window area : 0

a) warm period:

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.50 = 4.0 K.

no cool period calculation for this zone

Zone Type 2 - window area : 4 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.41 = 4.1 K

b) cool period

Φs = 3.28 (4) = 13.12 kWh, then swing = 13.12 (0.61) / 12.88 = 0.60 K

Zone Type 3 - window area: 9 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.30 = 4.2 K

b) cool period

Φs = 3.28 (9) = 29.52 kWh, then swing = 29.52 (0.61) / 12.62 = 1.4 K

Zone Type 4 - window area: 18 m^2

a) warm period

Φi = 36, then internal swing = 36 (0.61) / 5.10 = 4.3 K

b) cool period

Φs = 3.28 (18) = 59.04 kWh, then swing = 59.04 (0.61) / 12.15 = 2.9 K

Zone Type 5 - window area: 30 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 9193 =4.5 K

b) cool period

Φs = 3.28 (30) = 98.4 kWh, then swing = 98.4 (0.61) / 11.55 = 5.1 K

A3.2.3 Envelope Thickness: 0.40 m

Zone Type 1 - window area : 0

a) warm period:

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.10 = 4.3 K.

no cool period calculation for this zone

Zone Type 2 - window area : 4 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.02 = 4.4 K

b) cool period

Φs = 3.28 (4) = 13.12 kWh, then swing = 13.12 (0.61) / 11.16 = 0.70 K

Zone Type 3 - window area: 9 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.93 = 4.4 K

b) cool period

Φs = 3.28 (9) = 29.52 kWh, then swing = 29.52 (0.61) / 10.94 =1.6 K

Zone Type 4 - window area: 18 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.74 =4.6 K

cool period

Φs = 3.28 (18) = 59.0 4kWh, then swing = 59.04 (0.61) / 10.53 = 3.4 K

Zone Type 5 - window area: 30 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.50 = 4.8 K

b) cool period

Φs = 3.28 (30) = 98.4 kWh, then swing = 98.4 (0.61) / 10.01 = 5.9 K

A3.3 Brick Zone Types

A3.3.1 Envelope Thickness: 0.10 m

Zone Type 1 - window area : 0

a) warm period:

Φi = 36 kWh

and from equation (11): swing = 36 (0.61) / 5.16 = 4.3 K.

no cool period calculation for this zone

Zone Type 2 - window area : 4 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 5.08 = 4.4 K

b) cool period

Φs = 3.28 (4) = 13.12 kWh, then swing = 13.12 (0.61) / 8.70 = 0.90 K

Zone Type 3 - window area: 9 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.98 = 4.4 K

b) cool period

Φs = 3.28 (9) = 29.52 kWh, then swing = 29.52 (0.61) / 8.52= 2.1 K

Zone Type 4 - window area: 18 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.79 = 4.6 K

b) cool period

Φs = 3.28 (18) = 59.04 kWh, then swing = 59.04 (0.61) / 8.21 = 4.3 K

Zone Type 5 - window area: 30 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.55 = 4.8 K

b) cool period

Φs = 3.28 (30) = 98.4 kWh, then swing = 98.4 (0.61) / 7.80 = 7.6 K

A3.3.2 Envelope Thickness: 0.20 m

Zone Type 1 - window area : 0

a) warm period:

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.77 = 4.6 K.

Zone Type 2 - window area : 4 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.69 = 4.7 K

b) cool period

Φs = 3.28 (4) = 13.12 kWh, then swing = 13.12 (0.61) / 9.52 = 0.80 K

Zone Type 3 - window area: 9 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.60 = 4.8 K

b) cool period

Φs = 3.28 (9) = 29.52 kWh, then swing = 29.52 (0.61) / 9.32 = 1.9 K

Zone Type 4 - window area: 18 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.43 = 5.0 K

b) cool period

Φs = 3.28 (18) = 59.04 kWh, then swing = 59.04 (0.61) / 8.98 = 4.2 K

Zone Type 5 - window area: 30 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.21 = 5.2 K

b) cool period

Φs = 3.28 (30) = 98.4 kWh, then swing = 98.4 (0.61) / 8.53 = 7.0 K

A3.3.3 Envelope Thickness: 0.40 m

Zone Type 1 - window area : 0

a) warm period:

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.65 = 4.7 K.

no cool period calculation for this zone

Zone Type 2 - window area : 4 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.58 = 4.8 K.

b) cool period

Φs = 3.28 (4) = 13.12 kWh, then swing = 13.12 (0.61) / 8.70 = 0.90 K

Zone Type 3 - window area: 9 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.49 = 4.9 K

b) cool period

Φs = 3.28 (9) = 29.52 kWh, then swing = 29.52 (0.61) / 8.52 = 2.1 K

Zone Type 4 - window area: 18 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.32 = 5.1 K

b) cool period

Φs = 3.28 (18) = 59.04 kWh, then swing = 59.04 (0.61) / 8.21 = 4.3 K

Zone Type 5 - window area: 30 m^2

a) warm period

Φi = 36 kWh, then internal swing = 36 (0.61) / 4.11 = 5.3 K

b) cool period

Φs = 3.28 (30) = 98.04 kWh, then swing = 98.04 (0.61) / 7.80 = 7.6 K

See summary of temperature swing predictions by DHC calculations and SERI-RES simulations in tables A3-1 and A3-2.

Table A3-1
Estimated Internal Temperature Swing Concrete Zone Type

		warm period		*cool period*	
Envelope Thickness (m)	*Mass / Floor Ratio*	*Swing DHC K*	*Swing SERI K*	*Swing DHC K*	*Swing SERI K*
	4	3.9	5.3	-	-
	4.9	4.0	5.5	0.9	1.4
0.10	3.8	4.1	5.7	2.0	2.5
	3.7	4.2	6.1	4.12	4.4
	3.5	4.4	6.7	7.2	7.0
	4	4.0	4.4	-	-
	4.9	4.1	4.6	0.6	1.21
0.20	3.8	4.2	4.9	1.4	2.1
	3.7	4.3	5.3	2.9	3.7
	3.5	4.5	6.0	5.1	5.9
	4	4.3	4.2	-	-
	4.9	4.4	4.4	0.7	0.9
0.40	3.8	4.4	4.7	1.6	1.8
	3.7	4.6	5.2	3.4	3.4
	3.5	4.8	5.9	5.9	5.6

Table A3-2
Estimated Internal Temperature Swing Brick Zone Type

		warm period		*cool period*	
Envelope Thickness (m)	*Mass / Floor Ratio*	*Swing DHC K*	*Swing SERI K*	*Swing DHC K*	*Swing SERI K*
	4	4.3	11.4	-	-
	4.9	4.4	11.5	0.9	1.5
0.10	3.8	4.4	11.7	2.1	2.7
	3.7	4.6	11.9	4.3	4.8
	3.5	4.8	12.3	7.6	7.6
	4	4.6	4.8	-	-
	4.9	4.7	5.0	0.8	1.4
0.20	3.8	4.8	5.3	1.9	2.5
	3.7	5.0	5.8	4.2	4.4
	3.5	5.2	6.6	7.0	7.0
	4	4.7	4.7	-	-
	4.9	4.8	4.9	0.9	1.2
0.40	3.8	4.9	5.2	2.1	2.2
	3.7	5.1	5.8	4.3	5.9
	3.5	5.3	6.5	7.6	6.2

Table A4.1
DHC of Measured Buildings

Building	*Element*	*Area m^2*	*dhc* W/m^2K	*DHC* kW/K	*Total DHC* kW/K
	floor	99.03	21.01	2.08	
	wall	14.24	17.09	0.24	
	wall	14.24	17.09	0.24	
	wall	19.90	17.09	0.34	
Huelva	wall	5.41	17.09	0.09	
	wall	5.41	17.09	0.09	
	wall	5.41	17.09	0.09	
	wall	19.90	17.09	0.34	
	roof	99.03	18.79	1.86	5.39
	floor	58.50	22.94	1.34	
	ceiling	25.80	22.94	1.34	
	wall	8.25	20.44	0.17	
	wall	8.25	20.44	1.65	
	wall	35.90	20.44	0.73	
	wall	25.32	20.44	0.52	
Salteras	wall	2.80	20.44	0.06	
	wall	2.68	20.44	0.05	
	wall	2.68	20.44	0.05	
	wall	79.60	20.44	1.63	
	wall	6.10	20.44	0.12	
	roof	12.24	22.71	0.28	
	roof	19.61	22.94	0.45	
	roof	4.68	22.94	0.11	6.28
	floor	20.40	22.71	0.46	
	wall	2.10	12.38	0.03	
	wall	8.54	12.38	0.11	
	wall	15.12	18.17	0.27	
Tower	wall	7.64	18.17	0.14	
	wall	7.20	18.17	0.13	
	wall	3.00	12.38	0.04	
	wall	10.79	18.17	0.20	
	wall	0.80	12.38	0.01	
	roof	20.40	19.93	0.41	1.79
	floor	63.39	22.94	1.45	
	wall	24.80	17.26	0.43	
	wall	24.80	17.26	0.43	
	wall	19.00	17.26	0.33	
	wall	24.46	17.26	0.42	
	wall	2.32	17.26	0.04	
	wall	6.18	17.26	0.11	
Carmona	wall	8.06	17.26	0.14	
	wall	9.01	17.26	0.16	
	wall	196.28	17.26	3.39	
	wall	20.16	17.26	0.35	
	wall	7.01	17.26	0.12	
	wall	67.19	17.26	1.16	
	wall	52.64	17.26	0.91	
	roof	43.80	24.19	1.06	10.49

A4.2 Internal Temperature Swings

A4.2.1 Heat Gains Calculations

The gains by conduction were estimated using the heat loss coefficient of the buildings and the sol-air-temperatures to account for solar gains through envelope. This is given by:

$Ts = To + I \times a / fo$,

where,

Ts	= sol-air-temperature
To	= external air temperature
I	= incident radiation
a	= absorbance of the surface
fo	= surface conductance

heat loss coefficient (HLC) = UA (ΔT)

Building 1: Huelva

Ts	= 23.8 + (522 x 0.6) / 18
	= 41.2 °C
Ti	= 27.4 °C
UA	= 280 W/K
Φi	= 200 W (12 hrs) = 2400
Φc	= 280 (14) = 3920 (12) + 2400
	= 50 kWh
DHC	= 5.39 kW/K
swing	= 50 (0.61) / 5.39
ΔTi	= 5.65 K

Building 2: Salteras

Ts	= 22.0 + (522 x 0.3) / 18
	= 30.7 °C
Ti	= 23.6 °C
UA	= 220 W/K
Φc	= 220 (7.4) = 1628 (12)
	= 19.53 kWh
DHC	= 6.28 kW/K
swing	= 19.53 (0.61) / 6.28
ΔTi	= 1.9 K

Building 3: Tower

Ts	= 22.1 + (522 x 0.3) / 18
	= 30.8 °C
Ti	= 25.4 °C
UA	= 120 W/K
Φc	= 120 (5.7) = 684 (12)
	= 8.20 kWh
DHC	= 1.79 kW/K
swing	= 8.20 (0.61) / 1.79
ΔTi	= 2.7 K

Building 4: Carmona

Ts	= 21.0 + (522 x 0.3) / 18
	= 29.7 °C
Ti	= 23.4 °C
UA	= 450 W/K
Φc	= 450 (6.5) = 2925 (12)
	= 35.1 kWh
DHC	= 10.5 kW/K
swing	= 35.1 (0.61) / 10.5
ΔTi	= 2.1 K

Table A5.1
Diurnal Heat Capacities for Various Concrete Masonry Units

Unit Type	*Thickness* *m*	*Location*	*Direct dhc* W/m^2K	*Indirect dhc* W/m^2K
solid	0.15	exterior	60.98	23.96
	0.15	interior	38.15	22.93
	0.20	exterior	61.26	23.05
	0.20	interior	49.51	24.13
hollow	0.15	exterior	34.35	18.79
	0.15	interior	22.65	17.09
	0.20	exterior	34.46	18.56
	0.20	interior	25.55	17.37
with sand fill	0.15	exterior	41.16	20.38
	0.15	interior	32.02	21.12
	0.20	exterior	39.63	19.75
	0.20	interior	38.78	20.04
with mortar fill	0.15	exterior	58.25	23.56
	0.15	interior	37.24	22.71
	0.20	exterior	57.40	22.59
	0.20	interior	47.92	23.90

Converted to Metric units from [5]

Table A5.2
Diurnal Heat Capacities for Various Materials - W/m^2 K

	thickness	*granite*	*concrete*	*limestone*	*brick*	*adobe*
direct	0.025	15.33	14.19	15.89	12.49	11.35
	0.05	31.46	28.33	31.34	24.59	22.26
	0.07	45.99	33.00	44.28	29.55	30.66
	0.10	59.39	36.34	51.67	34.52	35.20
	0.15	73.81	49.65	52.81	41.05	34.35
	0.20	74.10	51.10	48.83	37.76	31.80
	0.30	67.07	45.70	47.07	36.62	31.17
	0.40	65.30	44.29	47.13	36.79	31.23
indirect	0.025	13.62	12.49	13.62	11.35	10.22
	0.05	21.80	18.10	21.07	18.34	17.03
	0.07	24.41	20.01	21.07	19.23	18.73
	0.10	25.55	21.92	21.07	20.16	19.36
	0.15	25.27	21.77	21.80	19.76	18.11
	0.20	24.42	21.46	20.95	18.62	17.32
	0.30	23.34	20.03	20.72	18.62	17.26
	0.40	23.28	19.93	20.78	18.17	17.26

A6 Estimation of Relative Humidity

The calculation of hourly internal relative humidity for the open and cellular plans used on the thermal simulations was carried out by relating the external relative humidity values with the internal production of moisture and the internal temperature. The total internal absolute humidity is given by,

$AHi = AHo + \Delta\ AH$

where,

AHi = internal absolute humidity (g/kg)
AHo = external absolute humidity (g/kg)
Δ AH = difference in absolute humidity (g/kg)

The first step was to estimate the internal production of moisture. This was followed by the introduction of the external relative humidity on the inside which depend on both, the internal temperature and the ventilation rate. In humid environments, 1 person produces approximately 150 g/h of moisture. The
ΔAH can be calculated from the equation:

$$\Delta AH = \frac{Wi}{\rho a\,(V * ac/h)}$$

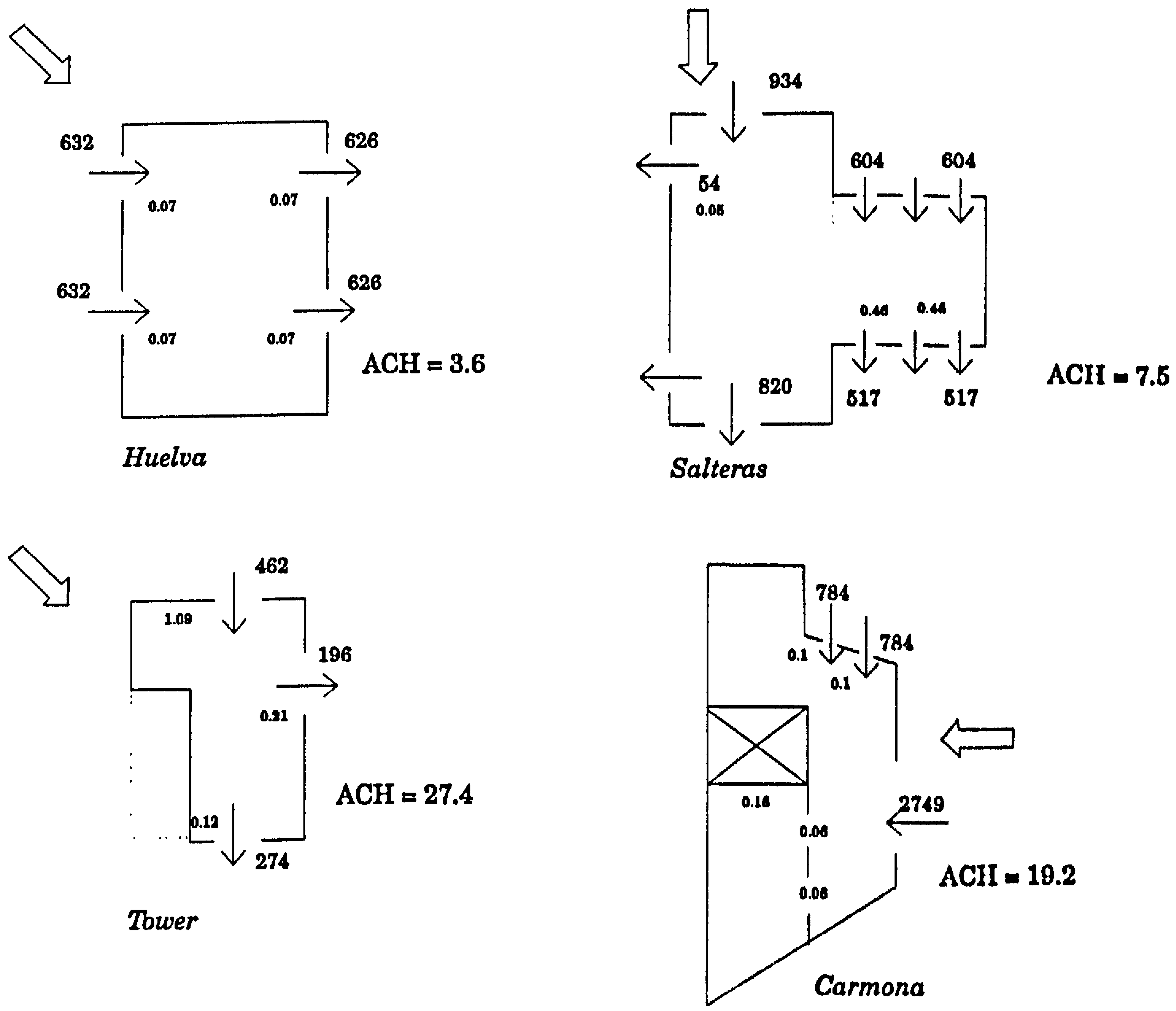
where,

Wi = internal moisture (g/h)
ρa = air density
V = room volume (m^3)
ac/h = air changes / hour

Calculation of internal absolute humidity in an room with 10 ac/h:

$$\Delta AH = \frac{150 \ \times 2_{\text{people}}}{1.3\,(43.2 * 10)} = 0.5 \text{ g/kg}$$

The resultant value was then be added to the external absolute humidity for each hour and then intercepted with the corresponding internal temperature on the psychrometric chart to obtain the internal relative humidity for each room.

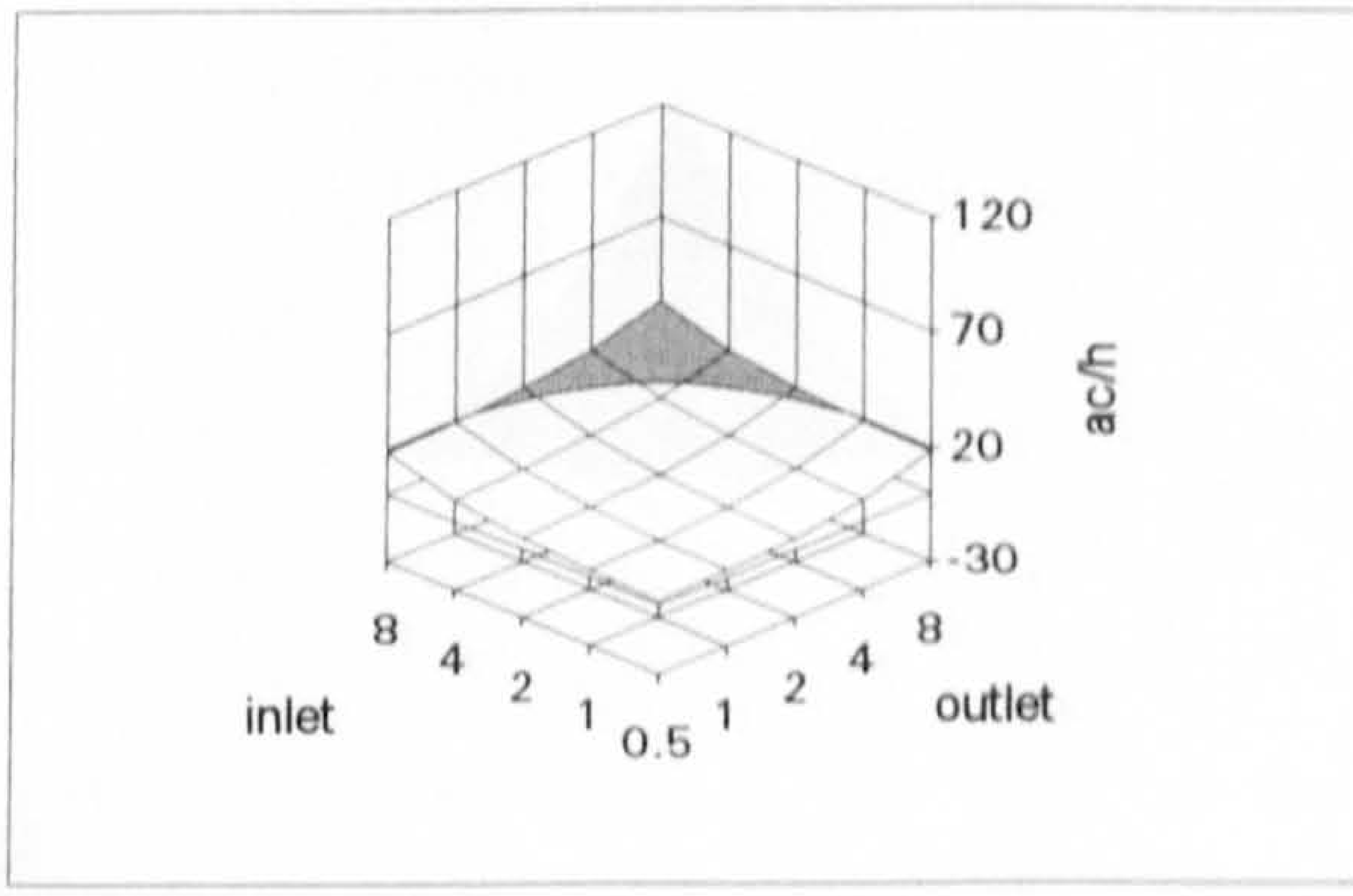


A7-1. Equivalent mass flow and pressure distribution for the four buildings. A wind speed of 1 m/sec was assumed in all buildings. The value shown in smaller fonts is the wind pressure given in Pascals and the larger values are the mass flow in m^3/hour. Table A5.1 shows the resultant air change rate for other wind velocities.

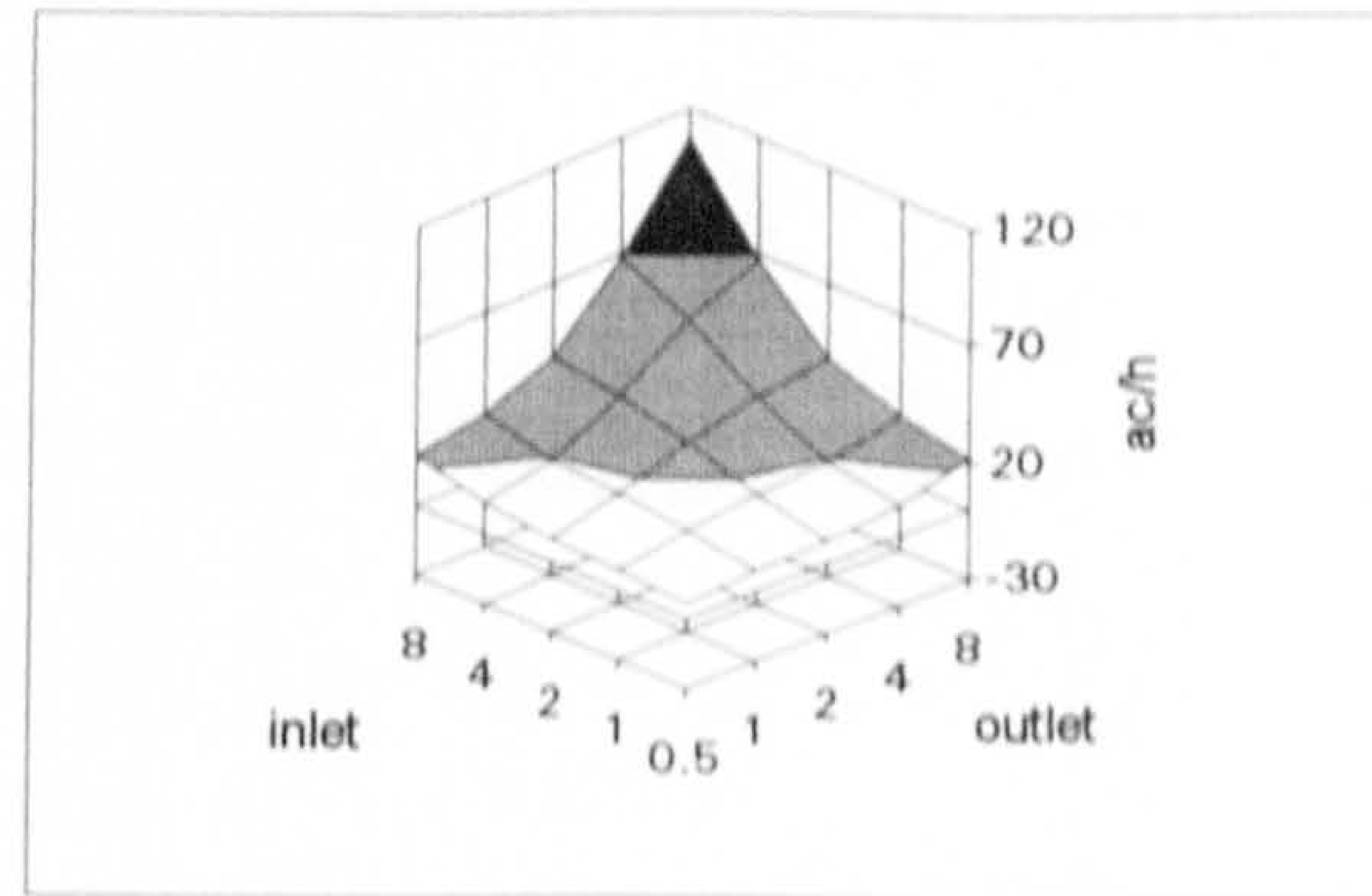
Table A7-1 Air Change Rates for Various Wind Velocities

Wind Speed	*Huelva*	*Salteras*	*Tower*	*Carmona*
0.5	2.5	4.7	26.2	17.8
1	3.6	7.5	27.4	19.2
1.5	5.7	10.2	34.1	18.9
2	7.6	13.1	42.8	23.6
3	11.5	18.7	64.3	37.5
5	19.2	30.0	108.2	67.3
7	26.8	41.5	151.7	96.0

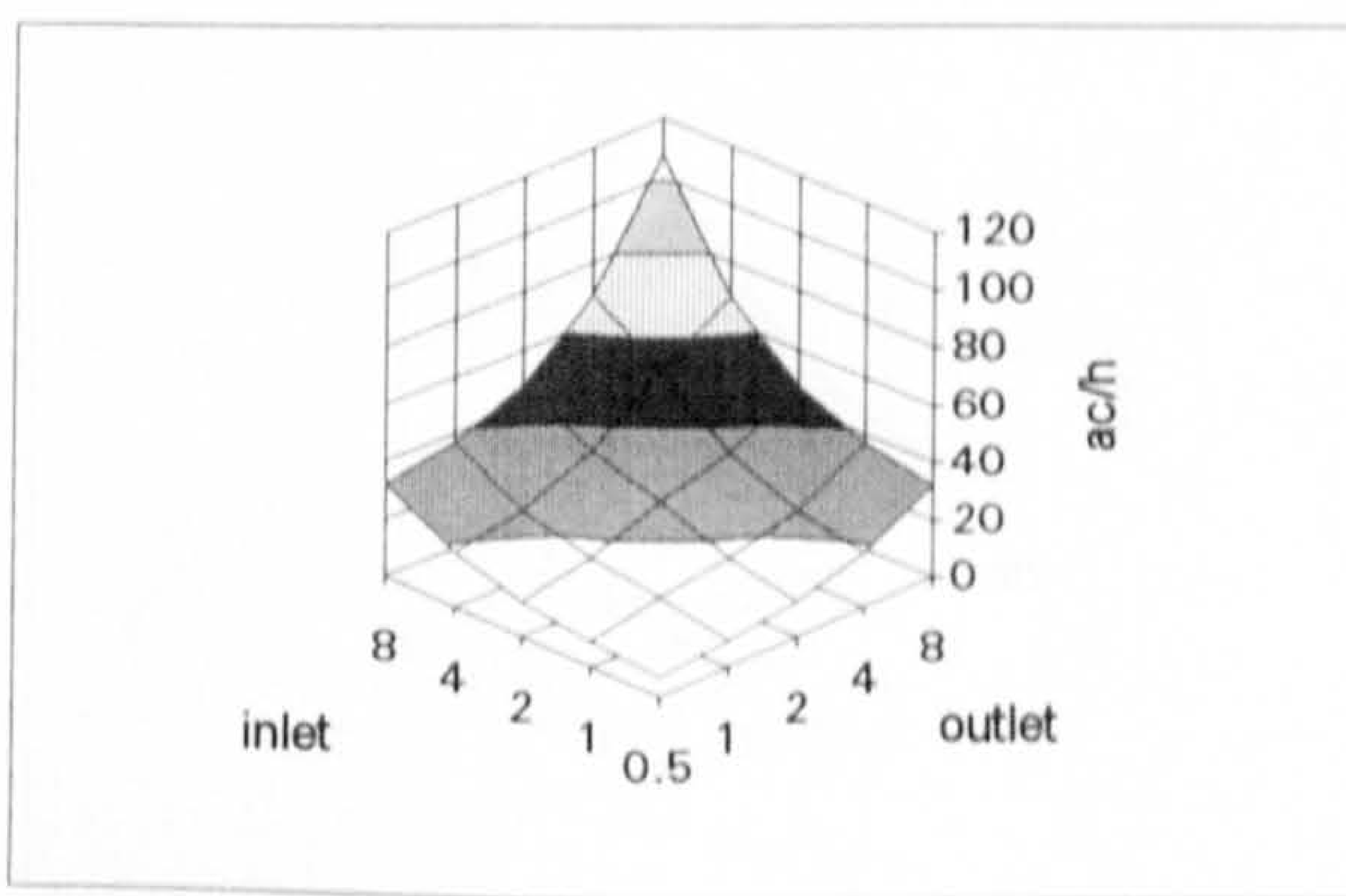
Based on BREEZE simulations



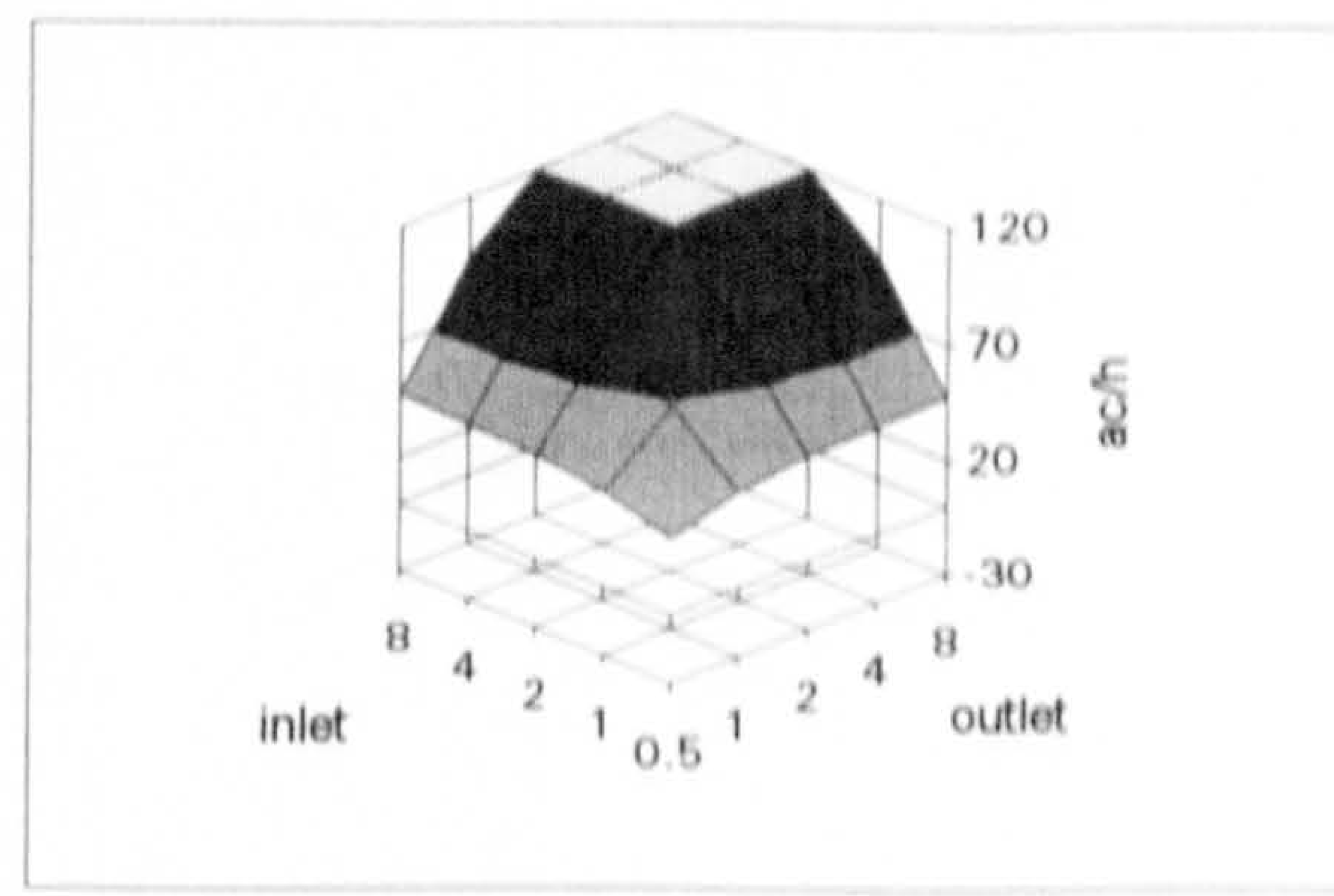
wind speed = 0 temp. difference = 2
wind direction = 90 height difference = 0



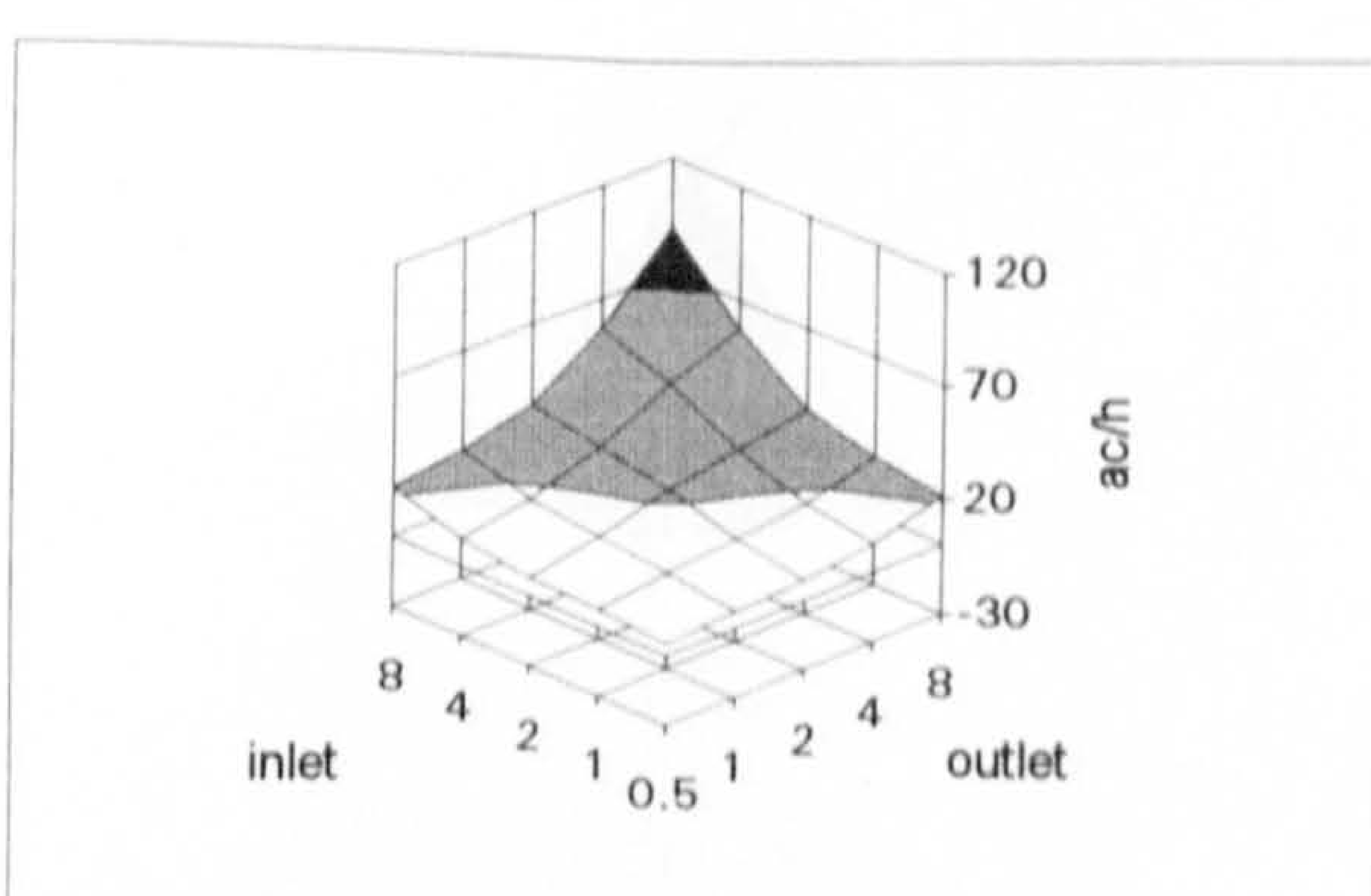
wind speed = 1 temp. difference = 5
wind direction = 90 height difference = 0



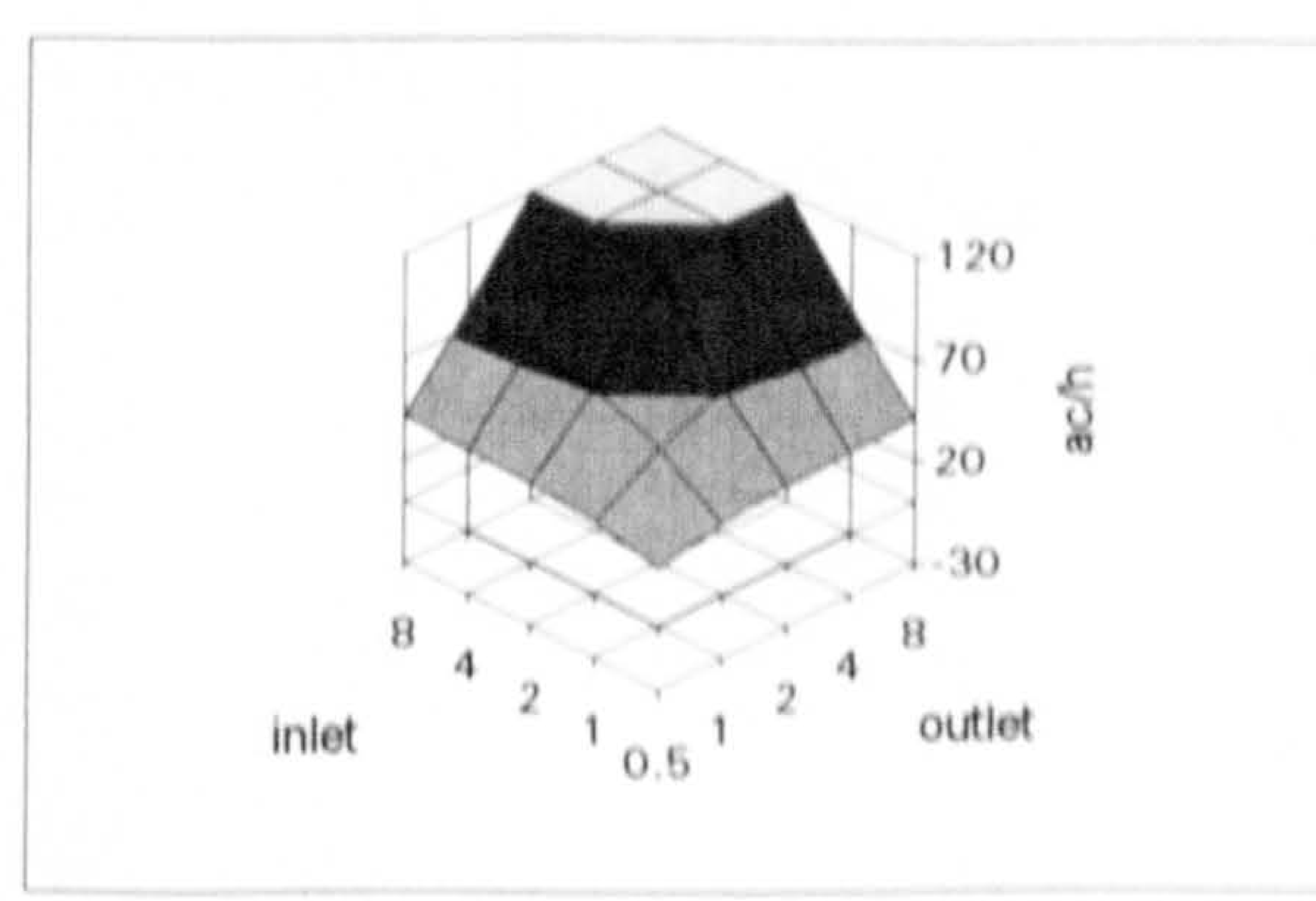
wind speed = 1 temp. difference= 2
wind direction = 90 height difference = 0



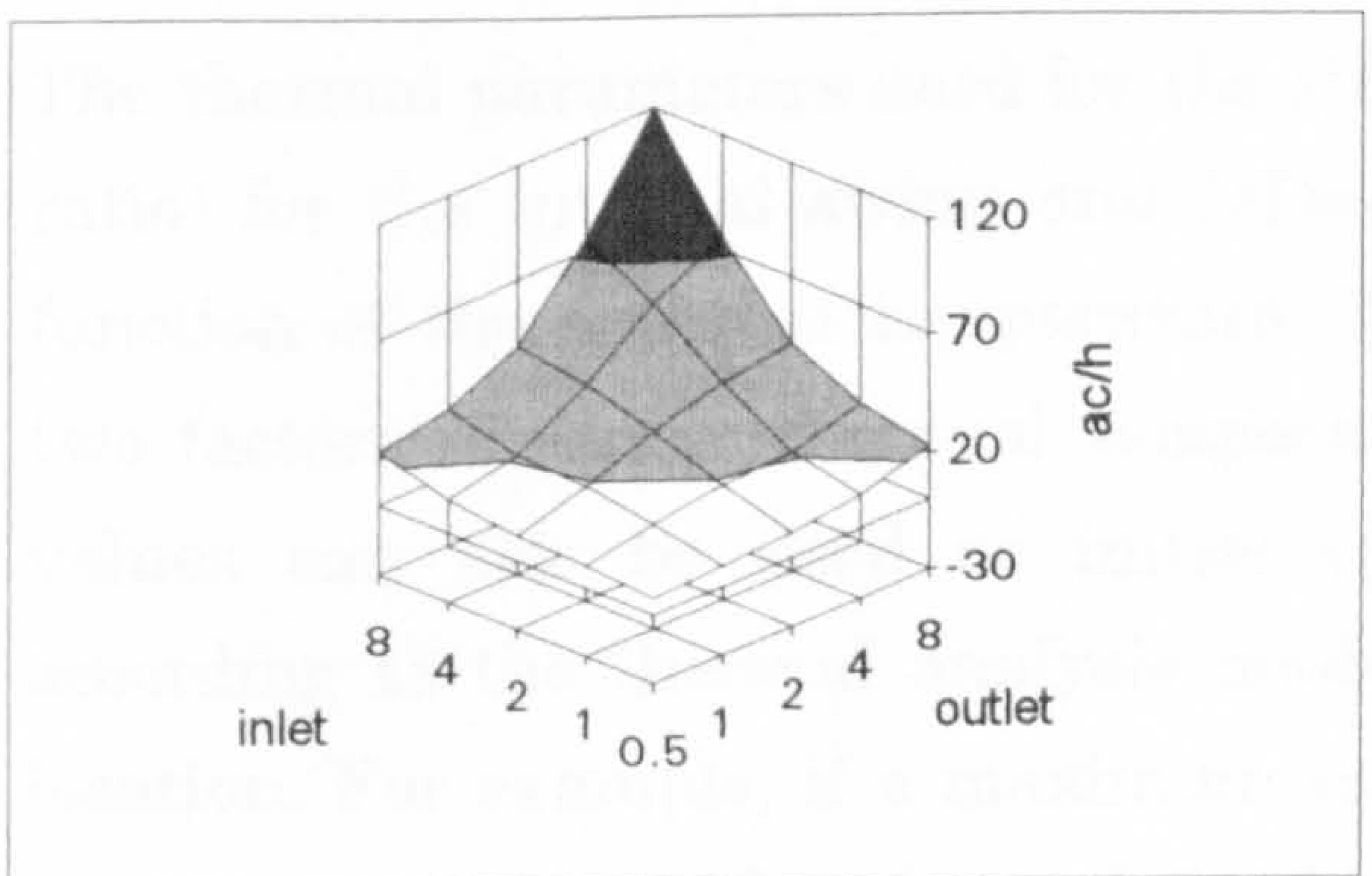
wind speed = 5 temp. difference = 2
wind direction = 90 height difference = 0



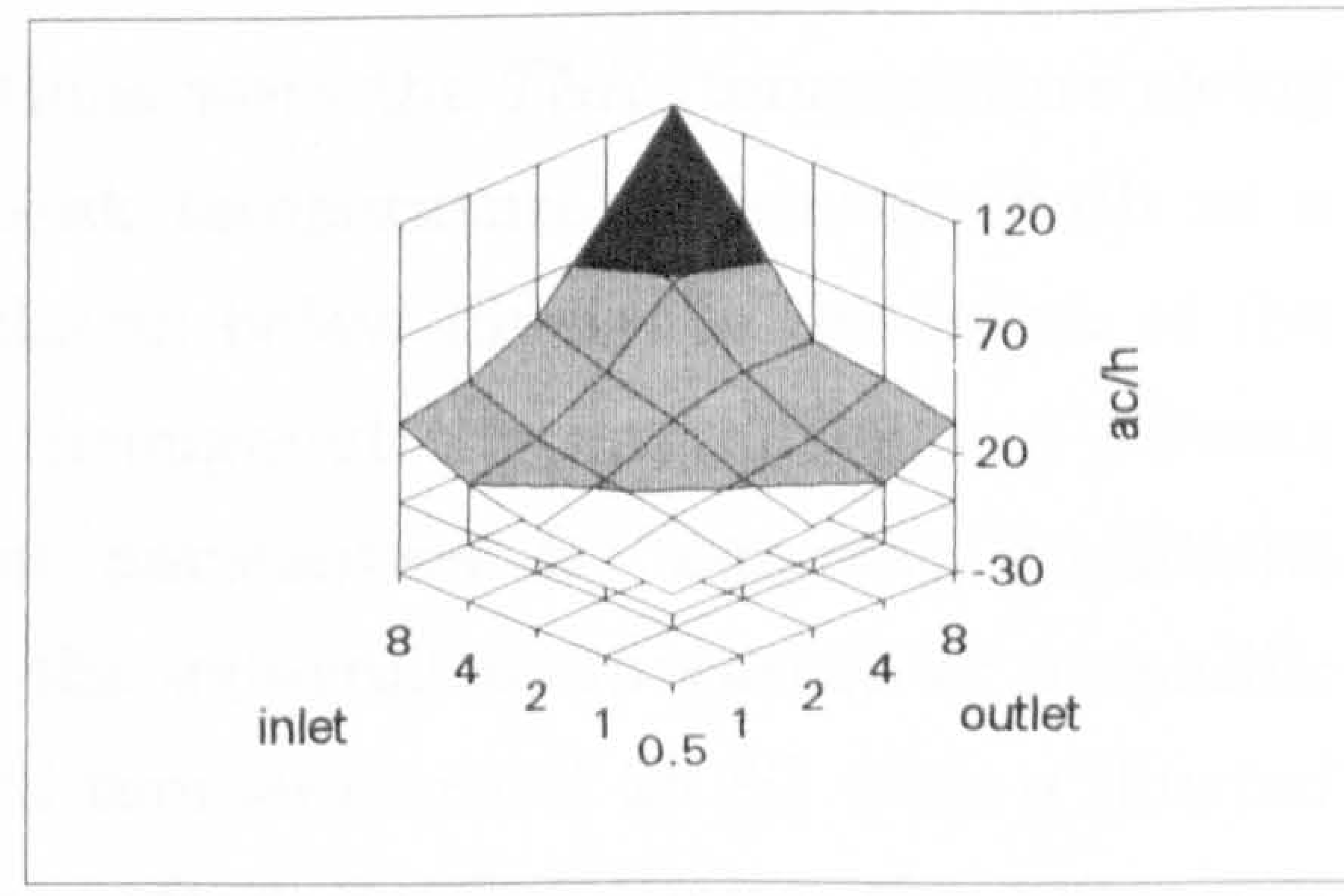
wind speed = 1 temp. difference = 2
wind direction = 45 height difference = 0



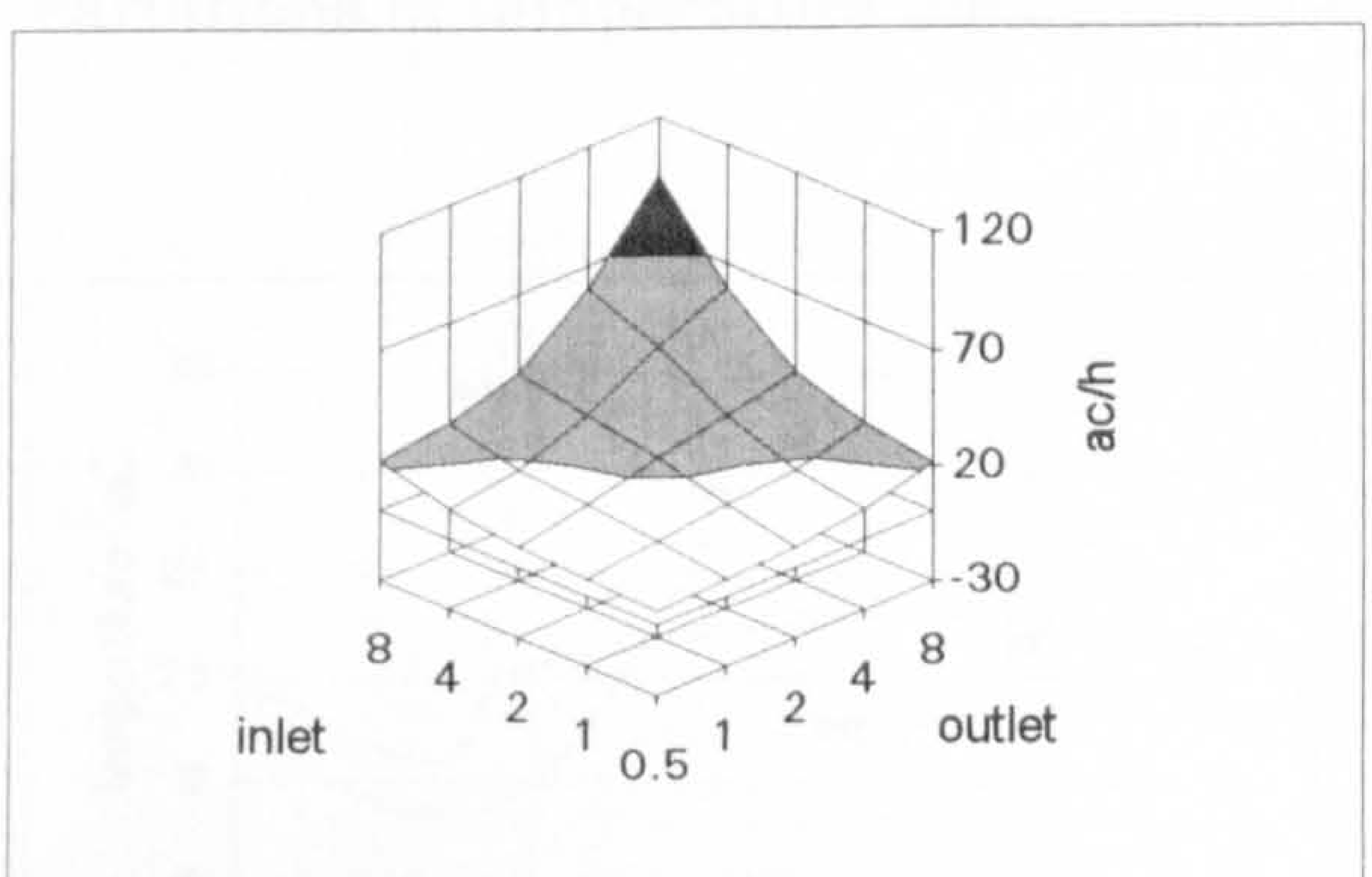
wind speed = 5 temp. difference = 2
wind direction = 45 height difference = 0



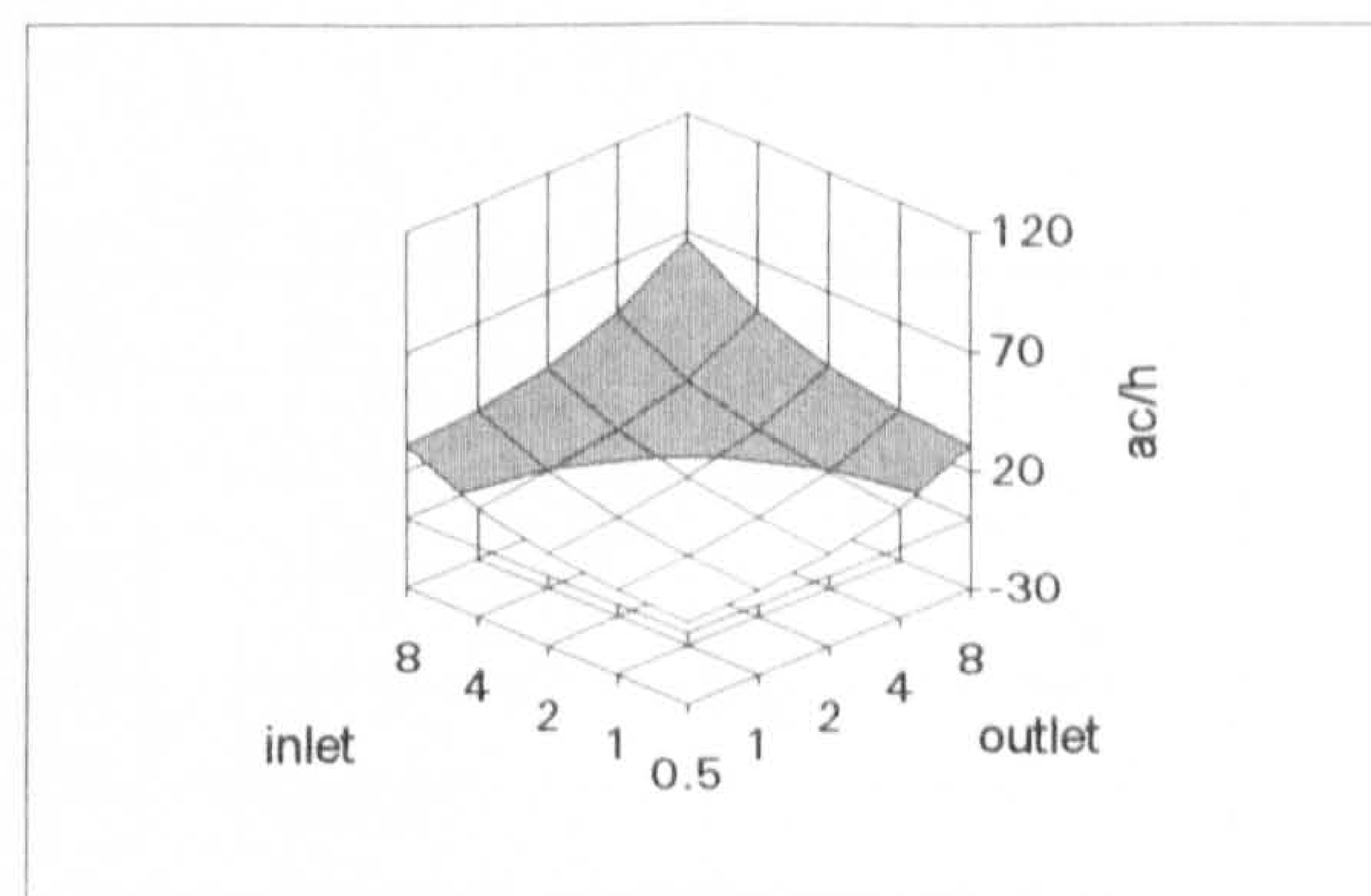
wind speed = 1 temp. difference = 2
wind direction = 90 height difference = 1



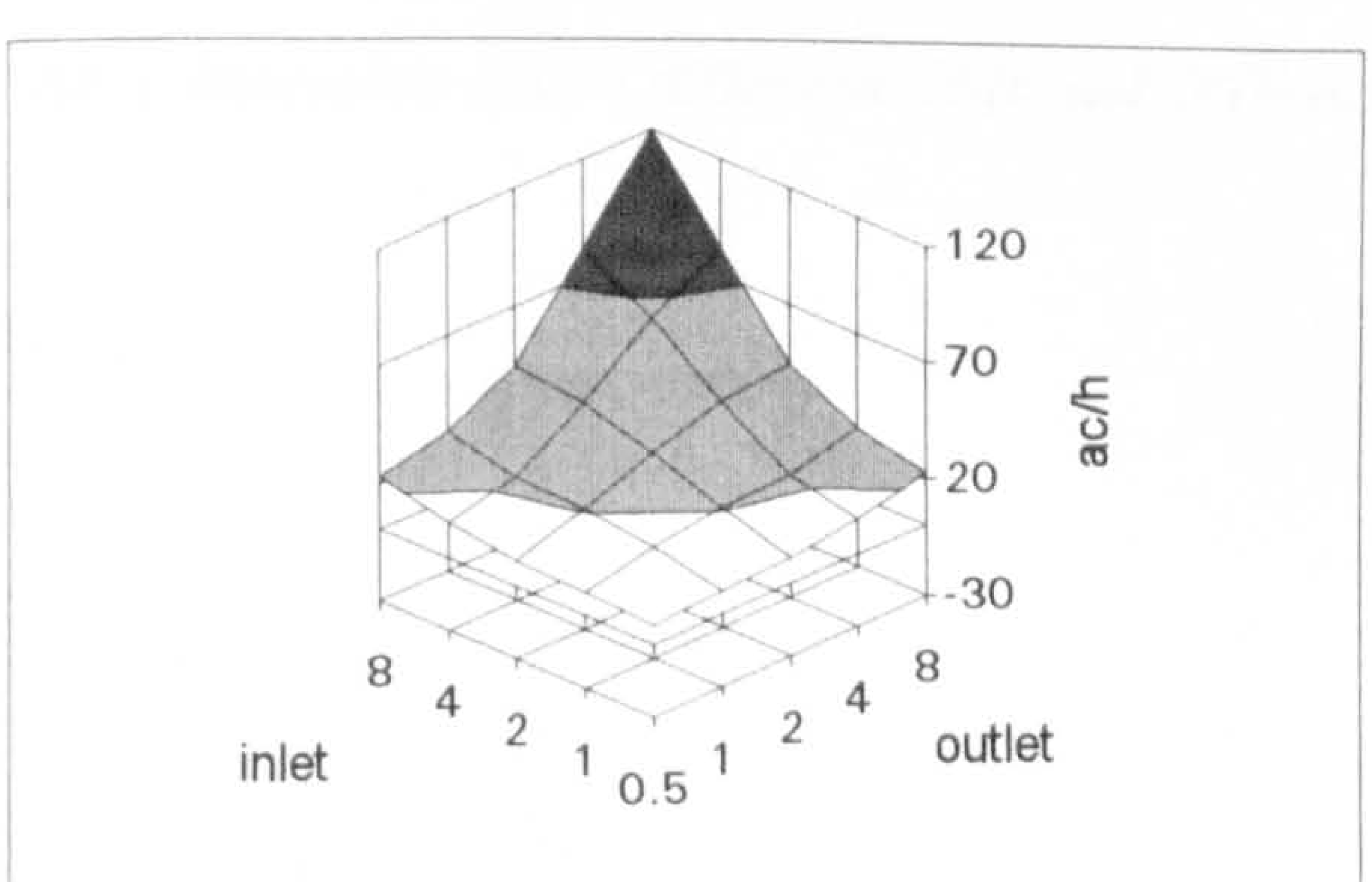
wind speed = 1 temp. difference = 5
wind direction = 90 height difference = 1



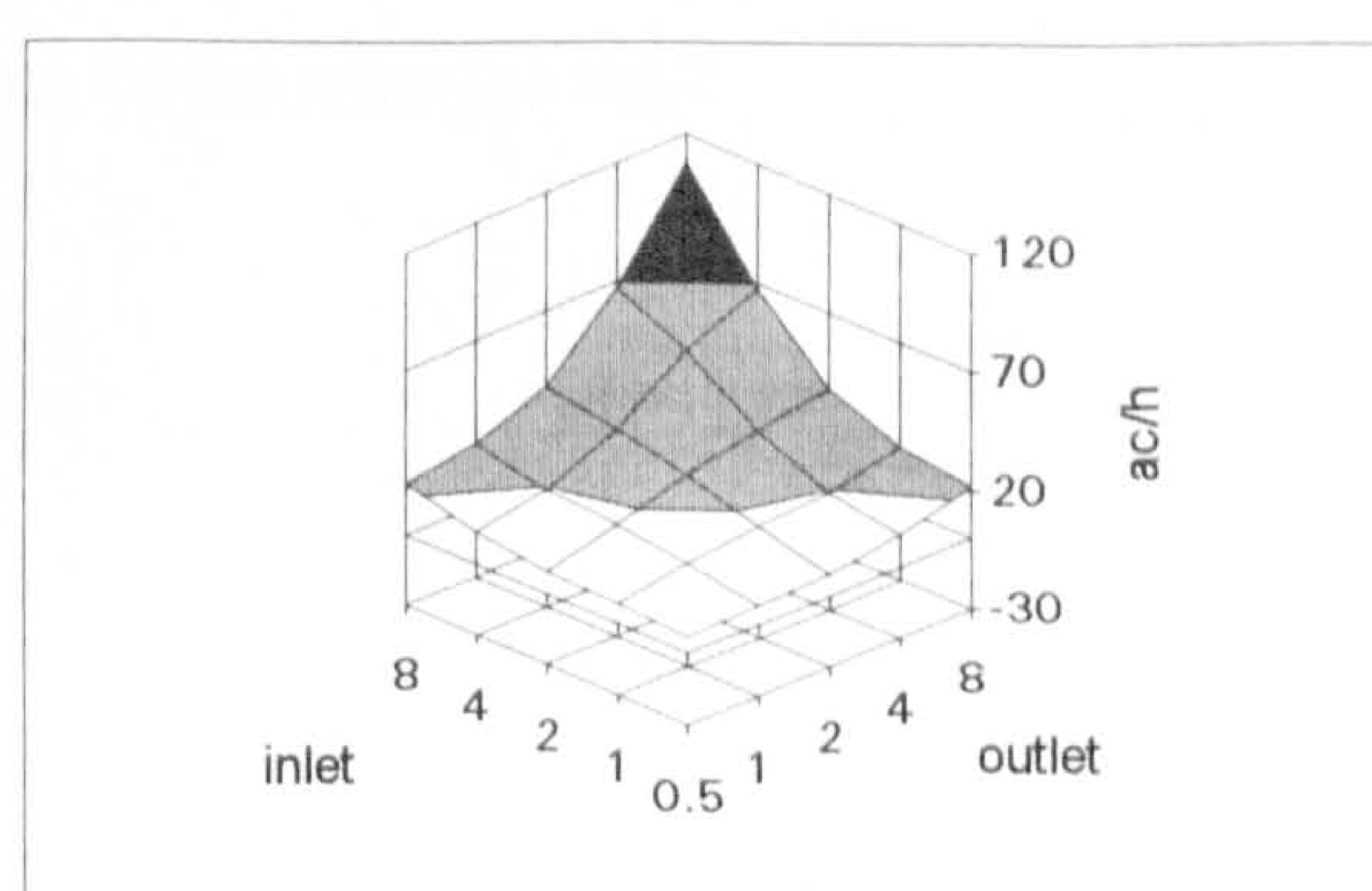
wind speed = 1 temp. difference = 5
wind direction = 90 height difference = 1



wind speed = 1 temp. difference = 5
wind direction = 90 height difference = 1



wind speed = 1 temp. difference = 2
wind direction = 90 height difference = 2

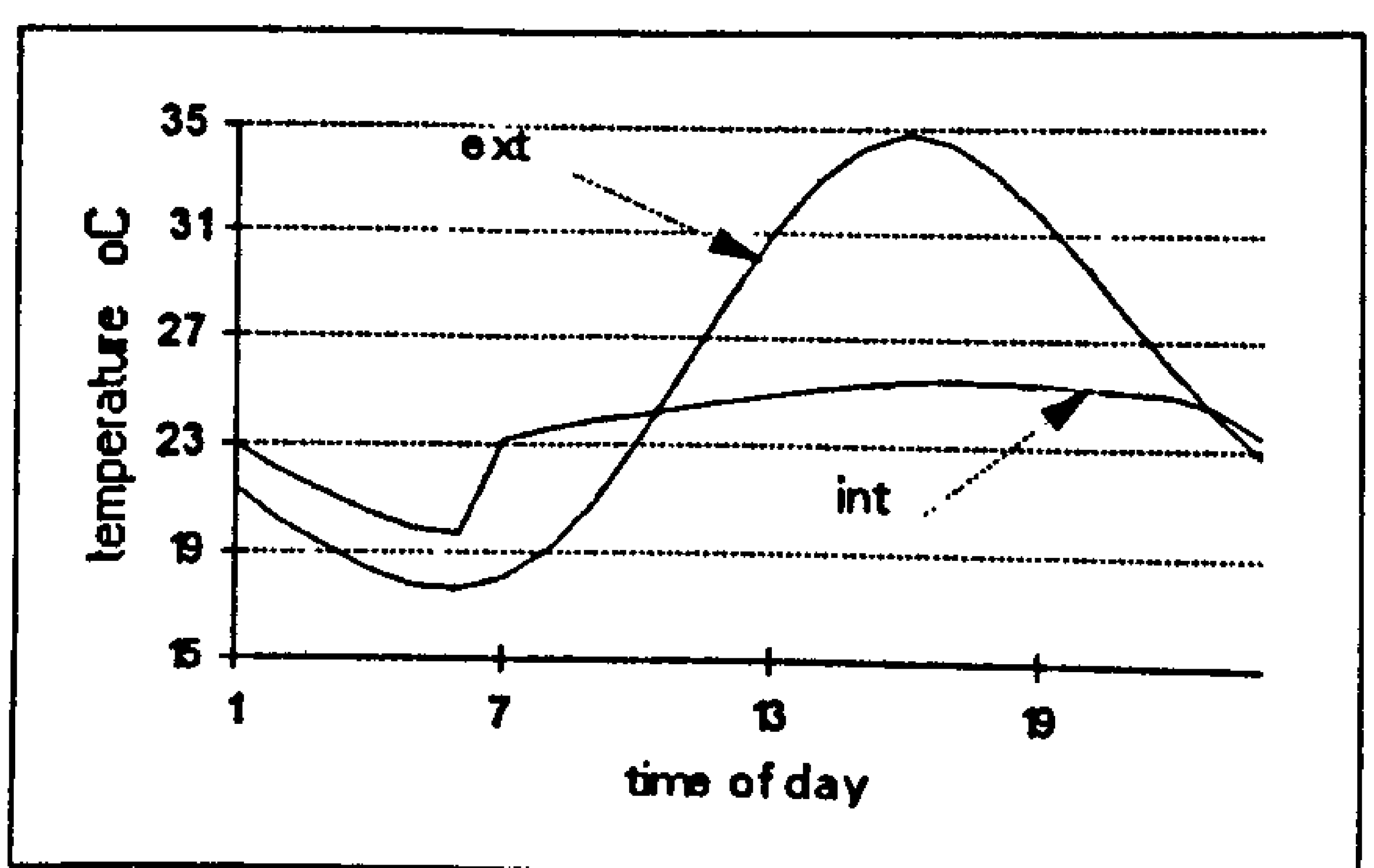


wind speed = 0 temp. difference = 2
wind direction = 90 height difference = 0

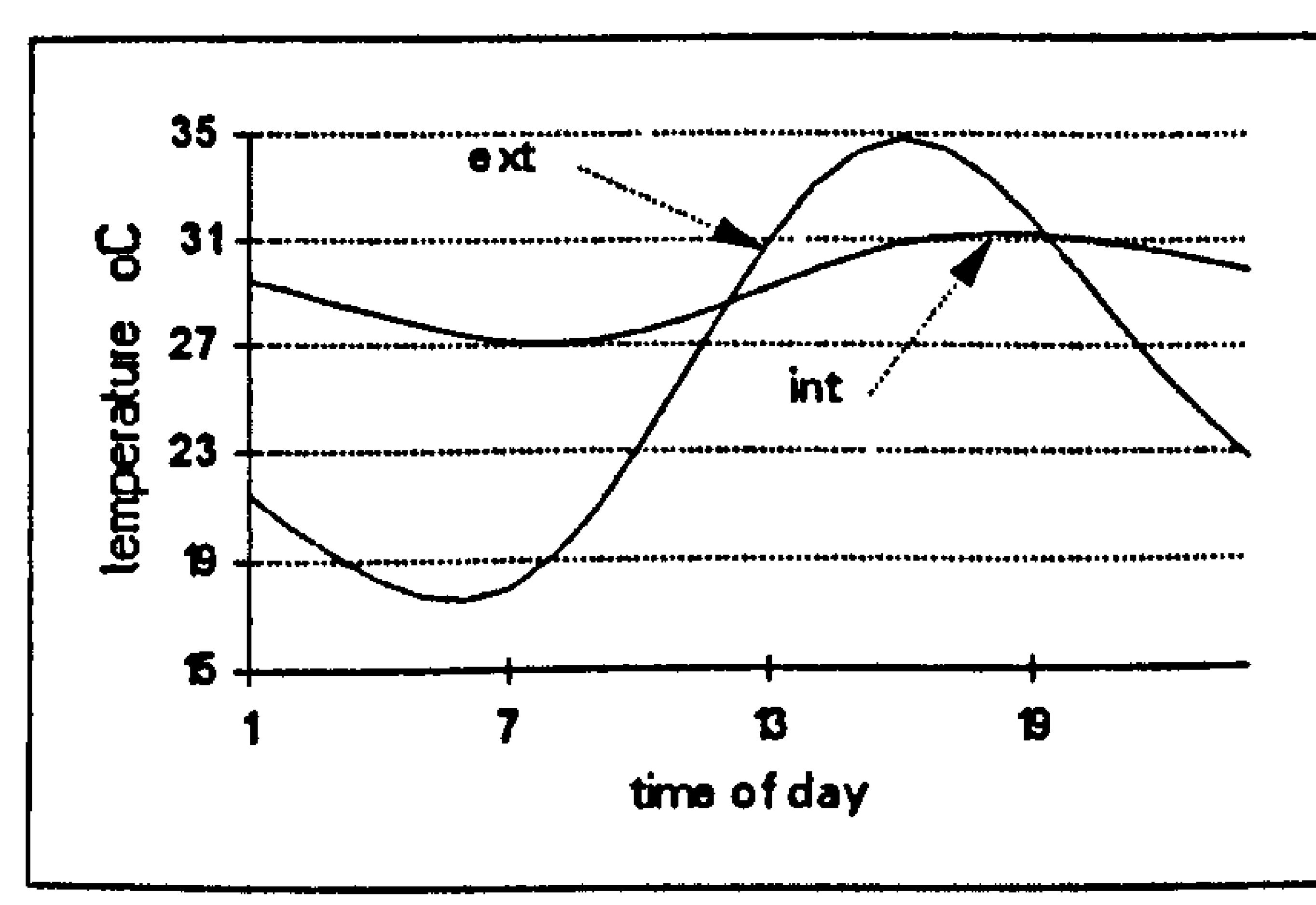
key:
wind speed (m/sec), temperature difference (deg K)
wind direction (degrees from inlet plane), window height difference (m)

A8.1 *TSR* and *DTmax* for Thermal Analysis

The thermal parameters used for the simulations were the *TSR* (temperature swing ratio) for the internal swing and *DTmax* (peak temperature difference) both as a function of the external temperature. The charts below illustrate the value of the two factors in terms of actual temperature throughout the day. *TSR* and *DTmax* values can also be used as initial comfort parameters for summer conditions according to the thermal analysis made for the external temperature of a specific location. For example, if a maximum internal temperature of 28 °C with a diurnal fluctuation of 5.5 K has been defined as the upper comfort limits, the minimum values to be set as targets using summer weather data for Seville would be *TSR* = 3 and *DTmax* = 6.5 K. Lower values than this would indicate overheating or excessive variations of temperature inside the enclosure.



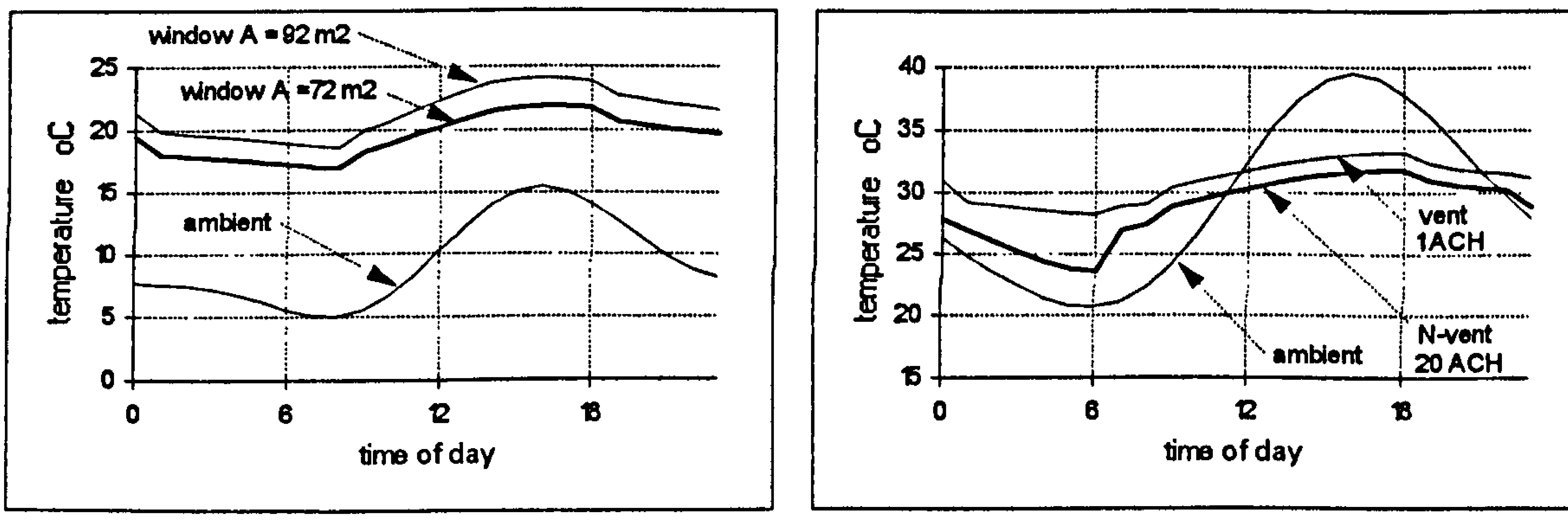
a) TSR = 3 DTmax = 9.4 K



b) TSR = 4 DTmax = 3.5 K

A8.1 Examples of two different *TSR* and *DTmax* results for the reference cube.

A9.1 Thermal and Daylight Results of Example Building
A9.1.1 SERI-RES Simulations



Run for January, mean ext = 9.4⁰C *b) Run for August, mean ext = 29⁰C*

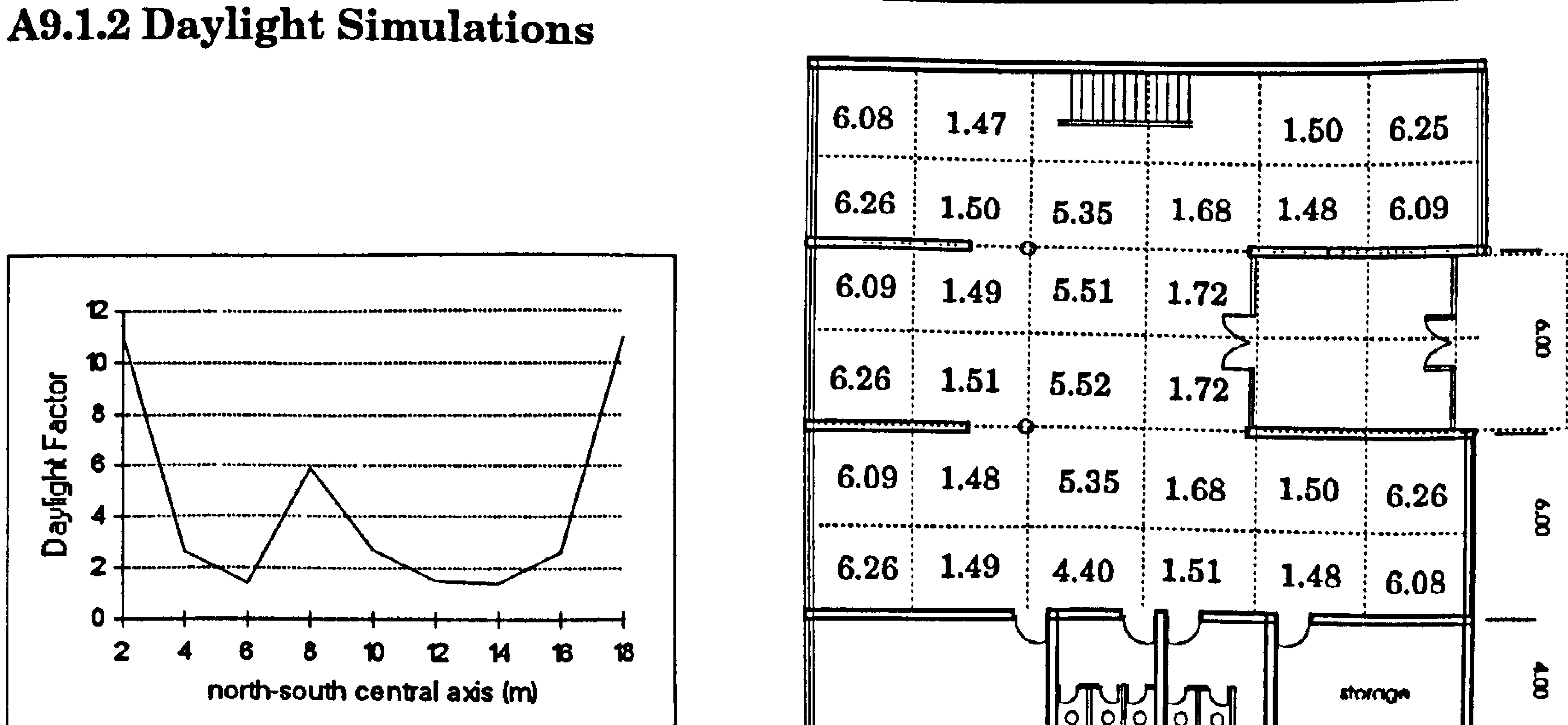
A9.1 Seri-Res results from simulations for the example building used in chapter 8. The results come within 1 to 1.5 degrees of difference with *dhc* predictions.

Table A9.1 Results of SERI-RES and DHC Calculations for Example Building

Jan	Window A = 72		Window A = 92		Aug	Vent = 1 ac/h		Vent = 20 ac/h	
	SERI	DHC	SERI	DHC		SERI	DHC	SERI	DHC
swing K	4.6	3.6	4.9	4.3		4.9	3.4	8.2	7.9
mean °C	20.3	19.8	22.1	21.7		30.9	31.7	28.8	28.6
peak °C	22.5	21.6	24.4	23.9		33.2	33.4	31.9	32.6

Estimates for Example Building (Office 2)
Warm Period: To = 28 °C, DHC = 30.82 kW/K, Φt = 172.49 kWh/day
for 1 ac/h, $\Delta Ti = 0.61 * 172.49/30.82 = 3.41$ K
Ti = To + h-gains/h-losses. To account for heat storage in mass,
Φt = h-gains - DHC * ΔTi /hlc, where, hlc = heat loss rate; then,
$Ti = 28 + (172.49 - 30.82 * 3.41)/24 / 1.151 = 30.4$ °C

A9.1.2 Daylight Simulations



a) Average daylight factors through central axis *b) Average daylight factors at plane = 0.95 m*

A9.2 Daylight simulations for the example building. The values assume overcast sky conditions.

Table A10.1
Magnitude and Phase for Various Dimensionless Thicknesses

ξ	Mag	Phase	ξ	Mag	Phase	ξ	Mag	Phase
.01	.014	90.0	.61	.828	76.3	1.42	1.118	47.0
.02	.028	90.0	.62	.839	75.9	1.44	1.115	46.7
.03	.042	90.0	.63	.850	75.4	1.46	1.111	46.4
.04	.057	89.9	.64	.861	75.0	1.48	1.107	46.1
.05	.071	89.9	.65	.872	74.6	1.50	1.104	45.8
.06	.085	89.9	.66	.883	74.1	1.52	1.100	45.6
.07	.099	89.8	.67	.894	73.7	1.54	1.096	45.3
.08	.113	89.8	.68	.904	73.3	1.56	1.092	45.1
.09	.127	89.7	.58	.914	72.8	1.58	1.089	44.9
.10	.141	89.6	.70	.924	72.4	1.60	1.085	44.7
.11	.156	89.5	.71	.934	71.9	1.62	1.081	44.6
.12	.170	89.4	.72	.943	71.5	1.64	1.077	44.4
.13	.184	89.4	.73	.952	71.0	1.66	1.074	44.3
.14	.198	89.3	.74	.961	70.6	1.68	1.070	44.1
.15	.212	89.1	.75	.970	70.1	1.70	1.067	44.0
.16	.226	89.0	.76	.979	69.6	1.72	1.063	43.9
.17	.240	88.9	.77	.987	69.2	1.74	1.060	43.8
.18	.254	88.8	.78	.996	68.7	1.76	1.057	43.7
.19	.269	88.6	.79	1.004	68.3	1.78	1.053	43.7
.20	.283	88.5	.80	1.011	67.8	1.80	1.050	43.6
.21	.297	88.3	.81	1.019	67.4	1.82	1.047	43.6
.22	.311	88.2	.82	1.026	66.9	1.84	1.044	43.5
.23	.225	88.0	.83	1.033	66.5	1.86	1.041	43.5
.24	.339	87.8	.84	1.040	66.0	1.88	1.039	43.5
.25	.353	87.6	.85	1.047	65.5	1.90	1.036	43.4
.26	.367	87.4	.86	1.053	65.1	1.92	1.033	43.4
.27	.381	87.2	.87	1.059	64.6	1.94	1.031	43.4
.28	.395	87.0	.88	1.065	64.2	1.96	1.029	43.4
.29	.409	86.8	.89	1.071	63.8	1.98	1.026	43.4
.30	.423	86.6	.90	1.076	63.3	2.00	1.024	43.4
.31	.437	86.3	.91	1.081	62.9	2.05	1.019	43.4
.32	.451	86.1	.92	1.086	62.4	2.10	1.015	43.5
.33	.565	85.9	.93	1.091	62.0	2.15	1.011	43.6
.34	.479	85.6	.94	1.095	61.6	2.20	1.008	43.7
.35	.493	85.3	.95	1.100	61.1	2.25	1.005	43.8
.36	.506	85.1	.96	1.104	61.1	2.30	1.002	43.9
.37	.520	84.8	.97	1.107	60.7	2.35	1.000	44.0
.38	.534	84.5	.98	1.111	60.3	2.40	.999	44.1
.39	.548	84.2	.99	1.114	59.9	2.45	.997	44.2
.40	.561	83.9	1.00	1.117	59.5	2.50	.996	44.3
.41	.575	83.6	1.02	1.123	59.1	2.55	.995	44.4
.42	.588	83.3	1.04	1.128	58.3	2.60	.995	44.4
.43	.602	83.0	1.06	1.132	57.5	2.65	.994	44.5
.44	.615	82.7	1.08	1.136	56.7	2.70	.994	44.6
.45	.628	82.3	1.10	1.138	56.0	2.75	.994	44.7
.46	.642	82.0	1.12	1.140	55.3	280	.994	44.7
.47	.655	81.7	1.14	1.142	54.6	285	.994	44.8
.48	.668	81.3	1.16	1.143	53.9	2.90	.995	44.8
.49	.681	81.0	1.18	1.143	53.3	2.95	.995	44.9
.50	.694	80.6	1.20	1.143	52.6	3.00	.995	44.9
.51	.707	80.2	1.22	1.142	52.0	3.10	.996	45.0
.52	.719	79.9	1.24	1.141	51.5	3.20	.997	45.0
.53	.732	79.5	1.26	1.140	50.9	3.30	.997	45.0
.54	.744	79.1	1.28	1.138	50.4	3.40	.998	45.1
.55	.757	78.7	1.30	1.136	49.9	3.50	.999	45.1
.56	.769	78.3	1.32	1.133	48.9	3.60	.999	45.1
.57	.781	77.9	1.34	1.131	48.5	3.70	.999	45.1
.58	.793	77.5	1.36	1.128	48.1	3.80	1.000	45.1
.59	.805	77.1	1.38	1.125	47.7	3.90	1.000	45.0
.60	.816	76.7	1.40	1.122	47.3	4.00	1.000	45.0

source: [5]